

MESON AND BARYON PRODUCTION IN PROTON-ANTIPROTON
AND PROTON-PROTON INTERACTIONS AT THE CERN INTER-
SECTING STORAGE RINGS.

BY

ULF MJÖRNMARK



LUND 1983

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BY

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Abstract This thesis gives measurements of inclusive production of rho, K^* (890) and phi as a function of transverse mass and incident energy. The cross-sections at rapidity = 0 are found to be independent of energy in the energy range studied. A comparison of meson and baryon production between pp- and $\bar{p}p$ collisions is done. Differences observed can be contributed to differences of the quantum numbers in the initial state. The studies were carried out using the Axial Field Spectrometer at the CERN Intersecting Storage Rings. This experiment is described.				
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THESIS
on
Meson and baryon production in proton-antiproton
and proton-proton interactions at the CERN
Intersecting Storage Rings

by

Ulf Mjörnmark
Elementary Particle Physics
Department of Physics
University of Lund
LUND

To MS and KH

Behind every successful man
stands a surprised woman

T. Dahmen

Outline of thesis

This thesis is based on the analysis of pp and $p\bar{p}$ interactions at the CERN Intersecting Storage Rings (ISR). It comprises the following papers:

- i) The Axial Field Spectrometer at the CERN ISR
H. Gordon et. al.
Nucl. Instr. Meth. 196 (1982) 303
- ii) A comparison of particle production in the central region of $p\bar{p}$ and pp collisions
at $\sqrt{s} = 53$ GeV
T. Åkesson et. al.
CERN-EP/83-75, to be published in Nucl. Phys.
- iii) Inclusive vector-meson production in the central region of pp collisions at $\sqrt{s} = 63$ GeV
T. Åkesson et. al.
Nucl. Phys. B203 (1982) 27
- iv) Inclusive vector-meson cross-sections for $|y| < 1$ at $\sqrt{s} = 53$ GeV and 63 GeV.
U. Mjörnmark, LUNFD6/(NFFL-7016)/
submitted to Physica Scripta

In section I a brief review of hadron spectroscopy is given. Section II contains a description of the experiment (paper I). In section III is a comparison between proton-proton and antiproton-proton collisions done (paper II), in section IV and V results on inclusive vector-meson cross-sections are presented (paper III and IV).



I Introduction

After the discovery of the pion in 1947, shortly followed by the discovery of the K-mesons, the new powerful proton accelerators produced a large number of new hadrons (strongly interacting particles). To bring order in the fast growing zoo of hadrons Gell-Mann and Neeman in 1964 applied unitary symmetry, $SU(3)$, to group related hadrons in families with well defined quantum numbers.

The fundamental representation of $SU(3)$ was proposed to correspond to physical states, the quarks. In the quark model a quark and an antiquark combines to form a meson and three quarks make up the baryons. At that time all known hadrons could be made up from three different kinds or flavours of quarks, namely, u (up), d (down) and s (strange) quarks. The s-quark, which is supposed to be the heavier of the three, gives the strangeness to the K-mesons. The quark model correctly predicted the existence of a new particle, Ω^- .

The discovery of the J/Ψ meson in 1974 and the T meson in 1977 forced the particle physicists to expand the quark family with the new flavours c (charm) and b (bottom) quarks. From symmetry reasons it is appealing to assume that there should exist as many fundamental quarks as leptons and therefore the search for another quark, the t (top) quark, is going on.

An important step towards verification of the quark model was the study of deep inelastic electron-proton scattering at Stanford. In this experiment electrons scattered from protons as if they scattered elastically from an object much smaller than the proton itself. This implies that the proton itself is composed of smaller objects (partons, quarks), in analogy with Rutherford's experiment 1911, where he revealed the atomic nucleus by irradiating a gold foil with alpha particles.

By using the information on the hadron structure from e.g. deep inelastic lepton-hadron scattering, attempts have been made to predict the distributions of produced particles. But measurements have shown that to explain the observed distributions of longlived particles (pions, kaons, protons), one must allow for a substantial production of heavier resonant particles. Hence resonance production will provide more direct information on the production mechanism in hadron collisions, than the study of pions and kaons. We have been able to study vector-meson production at the CERN ISR in both proton-proton and antiproton-proton collisions.

In addition to the production processes in $p\bar{p}$ collisions, there is one extra channel in $p\bar{p}$ collisions, namely the process where a quark from the proton and an antiquark from the antiproton are annihilating. By comparing $p\bar{p}$ and $p\bar{p}$ collisions one can investigate the importance of the annihilation channel. We have been looking for strong effects from the annihilation channel in inclusive hadron production, at higher energies than previously studied. Especially ψ -production may be sensitive to quark-antiquark annihilation. It is also interesting to look for quantum number effects, that reflects the fact that one of the incoming particles is an antiparticle in the case of $p\bar{p}$ collisions. It is known from previous experiments that in $p\bar{p}$ collisions an observed proton at $y=0$ is not always coming from pair creation, but is often associated with the incoming baryon number. This is further discussed in connection with paper II.

All hadrons studied in this thesis are in terms of the quark-model oldfashioned, i.e. built up by the u , d and s quarks and their antiparticles.

II The Axial Field Spectrometer

The Axial Field Spectrometer (AFS) is specially built to study large transverse energy phenomena in the central region at the energies available at the CERN ISR.

In ISR beamparticles can be circulating for several days. The storage ring consists of two rings, with very high vacuum, in which the particles circulate in opposite directions. They are brought to collide at eight intersection points, where the vacuum pipes cross each other at 13 degrees (fig 1). The highest available energy is 63 GeV in center of mass. This is achieved by accelerating particles to 26 GeV in the Proton Synchrotron (PS) and then injecting them into ISR where they can be accelerated to 31 GeV. Besides protons there have been stored deuterons, alpha particles and antiprotons.

The main part in AFS suitable for detection of collisions with large transverse energy is a 2π uranium/scintillator calorimeter. This was not completely installed at the time when paper I was published. Instead of a part of the calorimeter there was a cerenkov arm, consisting of aerogel (made by the Lund group), high pressure and atmospheric cerenkovs, for identification of high momentum particles. Between the cerenkov counters were proportional chambers. In this thesis however neither the uranium calorimeter nor the Cerenkov arm was used. The charged particles produced in the high energy collision are measured by a cylindrical drift chamber surrounding the beam pipes. The drift chamber is placed in an axially symmetric field of 0.5 T. Between the beam pipes and the drift chamber is a cylindrical hodoscope of scintillators ("Inner Hodoscope", IH). Along the downstream beam pipes are sets of scintillators placed ("Beam-Beam hodoscope", BB), which are used for luminosity monitoring (fig 2).

A coincidence between the Beam-Beam scintillators along both beam pipes, or as in paper III, a signal from the Inner Rodoscope was taken as a sign that a collision had occurred ("minimum bias") and triggered the readout system. More sophisticated trigger systems are also available, selecting more rare collisions, e.g. using the information from the drift chamber and proportional chambers in combination to select high momentum particles, the calorimeter information to select collisions with high transverse energy. These are described in some detail in paper II. But the results presented in this thesis are entirely based on the minimum bias trigger and the information from the drift chamber.

The drift chamber extends radially from 0.2 to 0.8 m, and is 1.4 m long. It is segmented into 88 4 degrees sectors, leaving holes of 16 degrees up and down to allow for supports to the beam pipes. Each sector has 42 layers of axial sense wires, which collect the ionization from a passing charged particle. For each wire the pulse heights from both ends are recorded. The signals are amplified by a preamplifier on the drift chamber and signals above a threshold are passed on to be shaped and digitized in Analog to Digital Converters (ADC). This information is used to determine the coordinate along the sense wire and to identify particles through ionization loss. A signal is also sent to a Drift Time Recorder (DTR). This measures the time it takes for the electrons from the ionization to drift towards the sense wire. In this way one can measure the drift distance, i.e. the distance between the sense wire and the place where the particle passed the wire, when one knows the velocity with which the electrons from the ionization is drifting towards the sense wires.

A fast processor reads only those DTR:s where data is recorded and all the ADC:s. From each DTR one gets a time information and an address, telling which wire it comes from. To each time information it finds the corresponding

ADC values. In this way the 7000 ADC values are reduced to a minimum. The corresponding ADC values are found through a 8k programmable look-up memory, using the address from the DTR. In order to optimize the off-line analysis the processor do also reorder the data into a format suitable for the pattern recognition program. The format is written into a 4k programmable memory, which means that the input/output format can be changed whenever desired.

After the reordering the data is read into the computer and then stored on magnetic tape. The computer system consists of 2 PDP 11/60, of which one reads the data and stores it on tape. The other computer can access an event through a link for monitoring the equipment. All calibrations and checking of processors and of the CAMAC system is also done with the monitor computer.

The tapes are analysed with a pattern recognition program (INGER) which finds tracks in the drift chamber from the digitizings. INGER finds track candidates basically by searching for straight rows of hits in a plane defined by radius and azimuthal angle. This information is then passed to the momentum determination program (MARTHA). MARTHA first finds the momentum from the points measured in the drift chamber (single fit momentum), using a quintic spline method. From the fit parameters the program then tries to find a common origin (vertex) of the tracks. The program first finds a vertex using well measured tracks. All other tracks may then be forced to be on this vertex. Including the vertex point, the program then makes a new momentum determination (vertex fit momentum).

IIIa A comparison between $\bar{p}p$ and pp collisions

The data used for this analysis consists of 172k $\bar{p}p$ and pp collisions each. The vertex found by the reconstruction program were required to lie within the interaction diamond, in order to reduce background from interactions with the residual gas in the vacuum chamber and with the beam walls. Collisions with no reconstructed vertex were not used in the analysis. After the vertex requirement there remains 127k $\bar{p}p$ and 129k pp events. In order to minimize differences due to changes in the system, the data were taken within one week. Since the pulseheights in the drift chamber may change with time, due to small variations in the high voltage, the pulseheights are adjusted such that the level for a minimum ionizing particle is the same for both data sets.

To get a sample of tracks that are well measured and belongs to the event, a set of selection criteria (cuts) were used to decide if a track should be used in the analysis or not. These cuts consists of the requirements that the track should point to the reconstructed vertex, have a reasonable number of measured points and the measurement errors to be small. For kaons and protons at least 10 pulseheight measurements were required, see below. All the results in the paper are insensitive to the cuts choosen, except the single particle spectra for the protons, where background from interactions in the material in front of the drift chamber becomes important. This background is negligible for the hardest cuts and is assumed to be the same for $\bar{p}p$ and pp . The cuts are choosen such that one gets a reasonable statistics and the resonances still can be seen by the naked eye.

Charged particles were identified by using the ionization information from the drift chamber. As a measure of the ionization the mean value of the 70% lowest pulseheight measurements is used (truncated mean pulse height) Fig 3

shows this value as a function of the logarithm of the momentum. Particles are identified down to a lower pulse height limit, which depends on the number of pulse height measurements. The lines in fig 3 shows the regions where particles are identified.

Particle production is studied for identified pions, kaons, protons and antiprotons. All ratios are normalized to the same number of events.

Effects from quantum number conservation are clearly seen, like the difference in K^+/K^- ratio from the change in associated kaon-hyperon production, e.g. the channel $p \rightarrow K^+ + \Lambda$ would be reduced in $\bar{p}p$ but $\bar{p} \rightarrow K^- + \bar{\Lambda}$ would be enhanced in $\bar{p}p$. There is also a difference in the rapidity distributions of protons and antiprotons in the central region, reflecting the incoming baryon number. The protons and antiprotons from the beams get pushed into the central region. No evidence for strong annihilation effects is observed. All major features, as the transverse momentum distributions and multiplicity distributions, are the same.

Invariant masses were formed by calling all charged particles a pion except when an identified particle was needed. The mass-spectra were divided into different transverse momentum and rapidity bins. The uncorrelated background below ϕ , K^* , ρ , f and Λ was subtracted by combining tracks from different events. For ψ no background subtraction is necessary since the signal is well defined above a small background. The resonance signals were extracted from fits using the CERN program MINUIT.

The fits used are:

$\phi : (x-a)**b*exp(-cx) + \text{Breit-Wigner}$
 $\rho : exp(-ax) + \text{Breit-Wigner}$
 $K^* : a + bx + \text{Breit-Wigner}$

φ $a + bx$ + Gaussian
 Λ $a + bx$ + Gaussian

where the first part is to describe the remaining correlated background and the second to extract the resonance signal. For φ , f and K^* the resonance mass was allowed to vary, while for φ and Λ the width was also a parameter in the fit.

With other parametrizations of the correlated background the amount of resonances change by 10-20 %. The different fits do in general change the amount of resonances by the same amount in pp and $\bar{p}p$, since the shapes of the spectra are similar. Hence the systematical errors of the ratios are smaller than the systematical errors from the individual fits (15-20% for φ and f , 10% for the rest of the particles). Again no differences between proton-proton and proton-antiproton reactions were observed. All the ratios are, within errors, equal to one. The distributions in transverse momentum and rapidity are all consistent with being equal, but the errors are quite large.

The associated production of kaons in events with a φ has also been studied. No sign of enhancement around φ is seen, but the errors are large. Extra particles with strangeness is expected if φ is produced through strange quark fusion (fig 4).

The conclusion from this analysis is that there are no differences between $\bar{p}p$ and pp collisions within the present statistical accuracy, except those expected from the differences in the incoming baryon number and charge. This does of course not exclude differences smaller than the errors in this analysis.

IIIb Stopping protons

It is clear from the rapidity distributions of protons and antiprotons that centrally produced low momentum protons/antiprotons are not only coming from pair creation, but is also coming from the incoming beam particles that are pushed into the central region. This may proceed by a process where they lose energy by emitting mesons and eventually appear as slow protons/antiprotons at 90 degrees. We refer to this process as stopping proton/antiproton.

It is interesting to see if there is a correlation between stopping both beamparticles. It is clear from the data that there is a signal for having both beam particles slowed down. The errors are very large, because of the subtractions to be made. A comparison with the proton and antiproton cross-sections as published by the British-Scandinavian group gave the acceptance for protons and antiprotons in pp collisions. There is no reason for the acceptance to be different in $\bar{p}p$. The acceptances are equal for protons and antiprotons, which indicates that there are no severe background problems in the proton sample. Using this acceptance for protons we get the cross-section $60 \pm 30 \mu\text{b}$ for the process where both beam particles are slowed down and appearing as protons. Since the stopped particle presumably equally well can be a neutron, the cross-section may be a factor four times higher for stopping both nucleons.

It is also shown that if there is a pair-creation process, the probability of having another pair-creation is decreased, as is the probability of having a stopped proton. It is emphasized that the region studied is restricted to rapidity less than 0.8.

If one thinks of stopping protons as a process where mesons are emitted, it may be that the multiplicity in events with a stopped proton is higher than in events with a proton from pair-creation. The study of the probability of pair-production and the probability of stopped proton does not show any strong difference in multiplicity dependence. There might, however, be a weak tendency for the probability of a stopped proton to rise faster with multiplicity than the probability for having a proton from pair-creation.

IV Vector-meson cross-sections at $\sqrt{s} = 63 \text{ GeV}$

The analysis is based on pp 200k collisions. Due to the high luminosity $2 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$, a large fraction of the events consists of more than one reaction. These events were rejected by using the timing information from the Inner Hodoscope. The final sample consists of 95k events.

Invariant masses of $\pi^+\pi^-$, $K^+\pi^-$ and K^+K^- were formed. Clear peaks are seen at the masses of ρ , K^* (890) and ϕ (1020). These were fitted with a P-wave Breit-Wigner with nominal masses and widths, together with an exponential non-resonant background function in the ρ case, and a linear for the other two.

The single particle acceptance was constructed by comparing the inclusive spectra to earlier published results. To translate single particle acceptances into vector-meson acceptances, a Monte-Carlo technique was used. Resonances were generated with a relativistic Breit-Wigner massdistribution, flat rapidity and azimuthal distributions, while the transverse momentum distributions were generated in accordance with the final result. The acceptances of the resonances were taken as the product of the probabilities of observing the decay products.

For all resonances, the data was subdivided in transverse mass intervals. For each bin the cross-sections were calculated using the acceptances as derived above. The values for K^* and ϕ were corrected for unseen decay modes (K^* decays into $K^+\pi^-$ in 67 % of the cases and 50% of the ϕ decay into K^+K^-). The transverse mass inclusive distributions are well described by a simple exponential with a slope of 6.4 ± 0.2 (GeV/c) for all resonances studied. The data can also be fitted to similar exponentials in p_T and p_T .

V Inclusive cross-sections for vector-meson production at $\sqrt{s} = 53$ GeV and 63 GeV

The acceptance for data on vector-meson production presented in paper II is evaluated and compared with results in paper III. An inconsistency was found which could be traced to an accidental extra factor 0.7 in the normalization of the cross-section as given in paper III. This being corrected, our data at $\sqrt{s} = 53$ GeV and 63 GeV are summarized and the ϕ cross-section is compared with other groups at larger rapidity.

Conclusions

Particle production in proton-proton and proton-antiproton reactions has been compared at $\sqrt{s} = 53$ GeV. The charged particle distribution is equal for transverse momenta below 5 GeV and for rapidity less than 0.6. Differences in the charged kaon and baryon production is observed, reflecting the difference in quantum numbers of the initial state. No difference is observed in the production of ρ , f , K^* , $\bar{K}^*$, ϕ , Λ and $\bar{\Lambda}$ between the two reactions.

Centrally produced baryons have been studied. A positive correlation between two stopping protons in proton-proton collisions was found.

The absolute inclusive cross-sections of ρ , $K^{\ast 0}$, $\bar{K}^{\ast 0}$ and ϕ have been measured at two different energies, $\sqrt{s} = 53$ GeV and 63 GeV. The inclusive transverse mass distributions at $\sqrt{s} = 63$ GeV are well described by an exponential with slope 6.4 ± 0.2 . There is no significant energy dependence of the cross-sections at $y = 0$ in the range covered by ISR.

Acknowledgements

I would like to express my gratitude to all my friends in the Axial Field Spectrometer collaboration and in particular the people at my home institute for their efforts and stimulation.

Special thanks goes to Anders Melin, for the work on the analysis and preparation of paper III, and B.S. Nielsen for close collaboration during my stay at CERN.

I would also like to thank all my friends, who have supported and have had patience with me during my studies.

To all of you from all of me : THANK YOU.

Figure captions

- fig 1) Layout of the ISR, showing the two intersecting rings and the injection paths from the PS.
- fig 2) Birds view of the AFS magnet with the Inner Rodoscope and Beam-Beam scintillators.
- fig 3) Truncated mean pulse height vs the logarithm of the momentum. The kaon and proton identification is indicated.
- fig 4) Production of ϕ through the creation of two ss pairs from the sea.

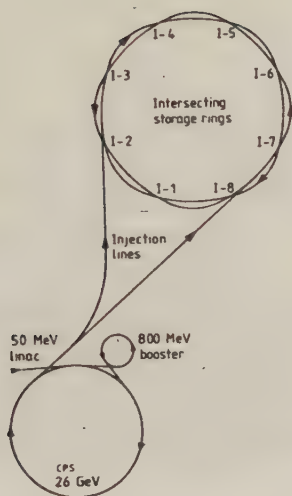


Figure 1

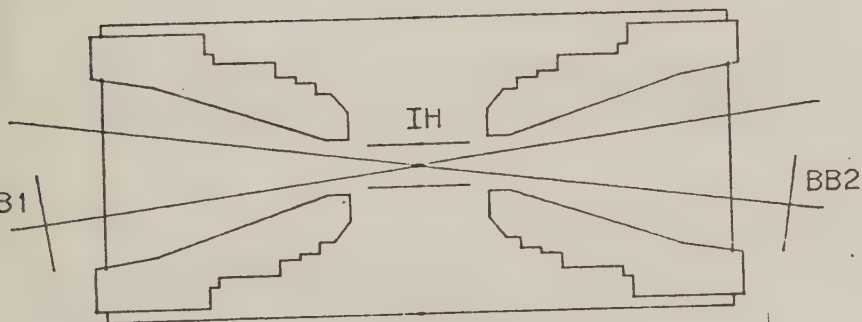


Figure 2

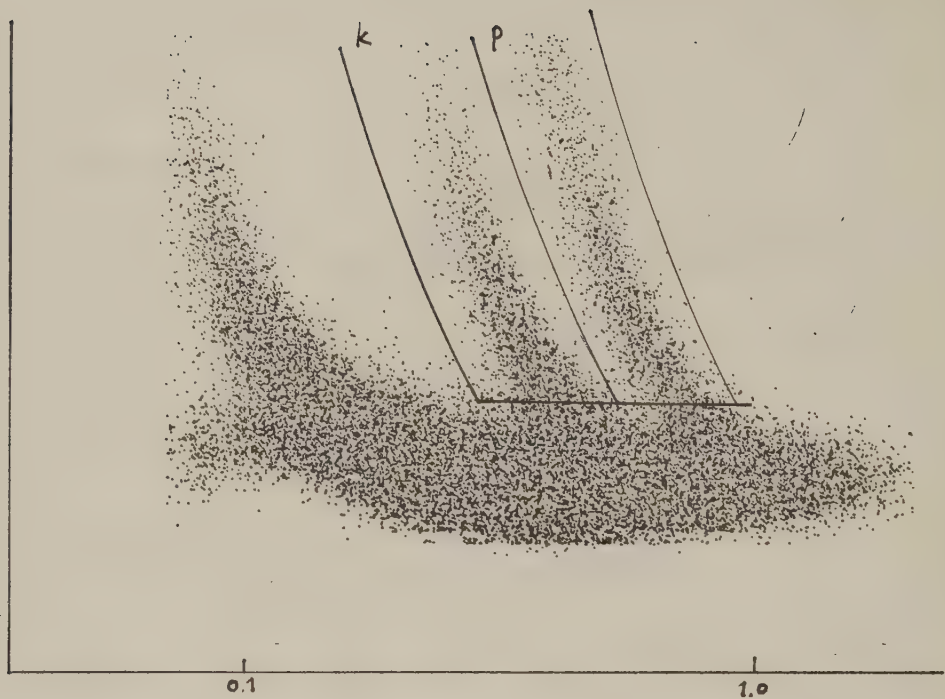


Figure 3

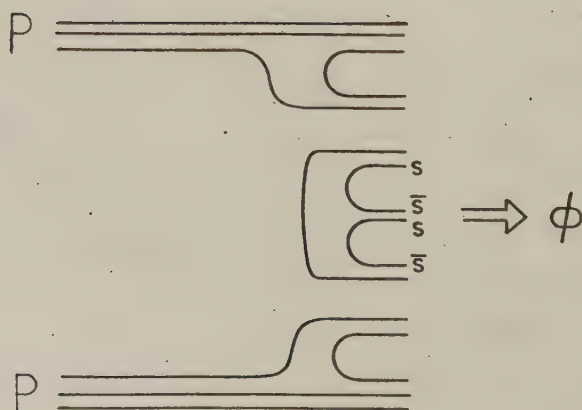


Figure 4

THE AXIAL FIELD SPECTROMETER AT THE CERN ISR

Brookhaven–CERN–Copenhagen–Lund–Rutherford–Tel Aviv Collaboration

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The axial field spectrometer is being exploited in a wide-ranging programme to study pp and pp-collisions which are characterized by a large transverse momentum. A specially shaped magnet together with an "imaging" drift chamber is used for efficient detection and momentum analysis of high multiplicity events at interaction rates of up to 5×10^6 s. Particle identification is accomplished over 1 sr; an uranium/scintillator hadron calorimeter will cover more than 8 sr in 1982 to provide an unbiased energy measurement.

1. Introduction

The axial field spectrometer (AFS) was recently brought into operation at the CERN ISR. It is being exploited in a wide-ranging programme to study different aspects of those proton–proton or proton–antiproton collisions which are characterized by a large transverse momentum (P_T). Examples include the measurement of inclusive distributions of identified high- P_T hadrons, and the study of event structures characterized by a large transverse energy (E_T) or the production of one or several high- P_T electrons or photons.

Our experimental approach to this programme em-

phasizes integration of advanced magnetic spectroscopy with state-of-the-art calorimetry. These techniques are fully exploited to provide the maximum information on all particles produced. In addition, information from these detectors is used in new ways for on-line event triggering and filtering; this allows even very rare events to be selected with high efficiency, an essential prerequisite for studies at a high-luminosity hadron collider, such as the ISR.

We aimed at considerable modularity of the detectors. Apart from clear advantages of construction, running, and servicing of such components, modularity provides us with ease for addition or reconfiguration of

our system to emphasize the study of specific final states. At present, for example, a 1 sr Cherenkov detector system allows hadron identification up to $p \approx 12$ GeV/c; liquid-argon electromagnetic calorimeters and a uranium-scintillator calorimeter ("hexagon") are used for a study of events containing direct photons.

2. AFS components and their performance

The 1981 layout of the AFS is shown in figs. 1 and 2. Fig. 2 also shows the recently installed low- β insertion, comprising a total of eight superconducting quadrupoles. These are the first superconducting beam elements to be used in a storage ring; they are now operational with colliding beams, producing a sixfold increase in luminosity.

2.1. The open axial field magnet

The design [1] contrasts with earlier magnetic spectrometers for ISR physics [2]*:

- a magnetic field integral of $0.5 \text{ T} \cdot \text{m}$ provides a momentum resolution of $\delta p/p = 0.01p$, which is satisfactory for our physics programme;
- the low field level facilitates the operation of the drift chamber and minimizes effects on the ISR beams, which traverse the field at an angle of $\pm 7.5^\circ$;
- it is easier and cheaper to construct and more reliable to operate;
- it facilitates the implementation of item (b);

b) Its unique form (fig. 3) reflects our insistence on integrating the magnetic spectrometer with the surrounding detectors (calorimeters, Cherenkovs) by maximizing the totally unobstructed aperture for particle detection, even in the forward direction:

azimuthal coverage: $0 \lesssim \phi \lesssim 2\pi$,

polar coverage: $0 \lesssim \theta \lesssim 15^\circ$ and $40^\circ \lesssim \theta \lesssim 140^\circ$.

c) It allows very rapid access (within 5 min) to the complex central detector; this is crucial for the ISR, which is operated continuously, except for very short (~ 2 h) interruptions that are several days apart. It allows access to the vacuum pipe in about one hour of time, if machine intervention (vacuum, etc.) becomes necessary.

The level and direction of the magnetic field is also shown in fig. 3.

Over the volume of the vertex detector the field is azimuthally symmetric to better than 0.5%; the field

integral transverse to the particle direction as a function of polar angle is shown in fig. 4; approximately constant momentum resolution is achieved for particles of a given P_T for polar angle in the range $45^\circ < \theta < 135^\circ$.

The magnet is operated routinely with either polarity, at a single nominal field level. The field component affecting the circulating beams is corrected using dipole compensator magnets on either side of the spectrometer; by raising and lowering the excitation currents simultaneously it is possible to turn the magnet on and off with stored beams, a feature which is used for checks. The total power consumption of the magnet system is 700 kW.

2.2. The vertex detector

For completeness we summarize the salient features and refer for more details to an extended discussion given elsewhere [3]. The physics programme and the high-interaction rate environment dictated the design considerations. In particular, the detector was optimized for efficient registration and analysis of final states with high multiplicity and high particle density ("jets") [4]. This is accomplished by highly redundant non-projective track-point measurements. The azimuthal coordinate perpendicular to the magnetic field is measured using drift techniques, whereas the coordinate along the drift wire is obtained with the charge-division method [5]. The 140 cm long cylindrical chamber (inner active radius 21 cm, outer active radius 80 cm) is organized in 4° sectors, with $100 \mu\text{m}$ Cu-Be wires serving as the sector-separating cathodes. Along the radius of such a sector a total of 42 drift wires ($30 \mu\text{m}$ diameter) measure the track position.

The performance, obtained in high luminosity ISR running (interaction rate $\gtrsim 800 \text{ kHz}$), is at present found to be:

σ (drift) = $200 \mu\text{m}$,

σ (charge division) = 1.5 cm (at a gas gain of about 2×10^4),

$\sigma(dE/dx) = 11\%$ (truncated mean on tracks with more than 30 ionization measurements),

$\Delta P_T/P_T \approx 0.02 P_T$ (for tracks with more than 35 drift measurements).

Mechanically, the chamber is executed as two semi-cylinders. This allows rapid extraction of the chamber from the magnet gap, without the need for breaking the ISR vacuum of 10^{-12} Torr. Each half chamber is mounted on a "transparent" support, which also carries 3444 twisted-pair cables from the chamber preamplifiers and which in turn is riding on one half of the "bottom" uranium calorimeter (see fig. 5). Drift chambers and calorimeters are supported by a chariot riding on precision rails, which ensures positioning of such an assembly with a reproducibility of $\approx 100 \mu\text{m}$.

* It conforms, however, to even earlier investigations as summarized by the 12th century scholar William of Occam: "It is in vain to do with more what can be done with less".

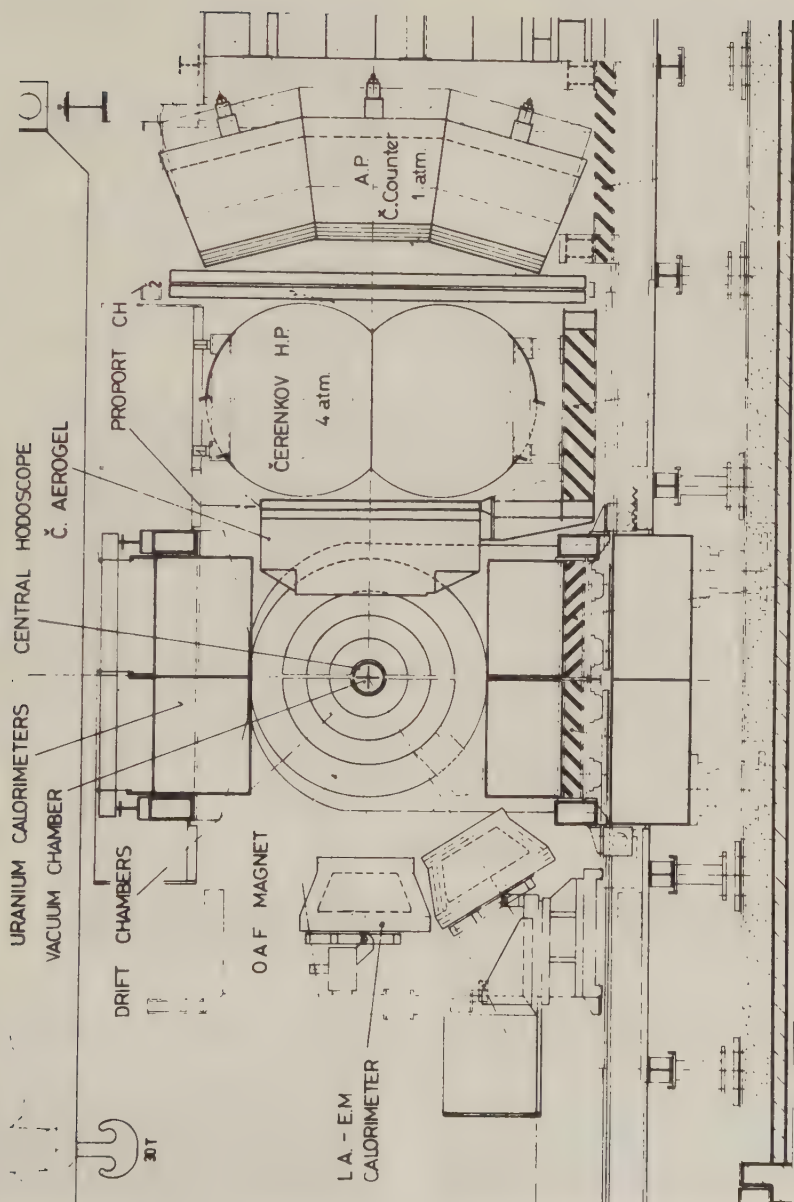


Fig. 1. Cross-section through the AFS (1981 configuration). The top and bottom U calorimeters (4 sr total) are being installed during the first half of 1981.

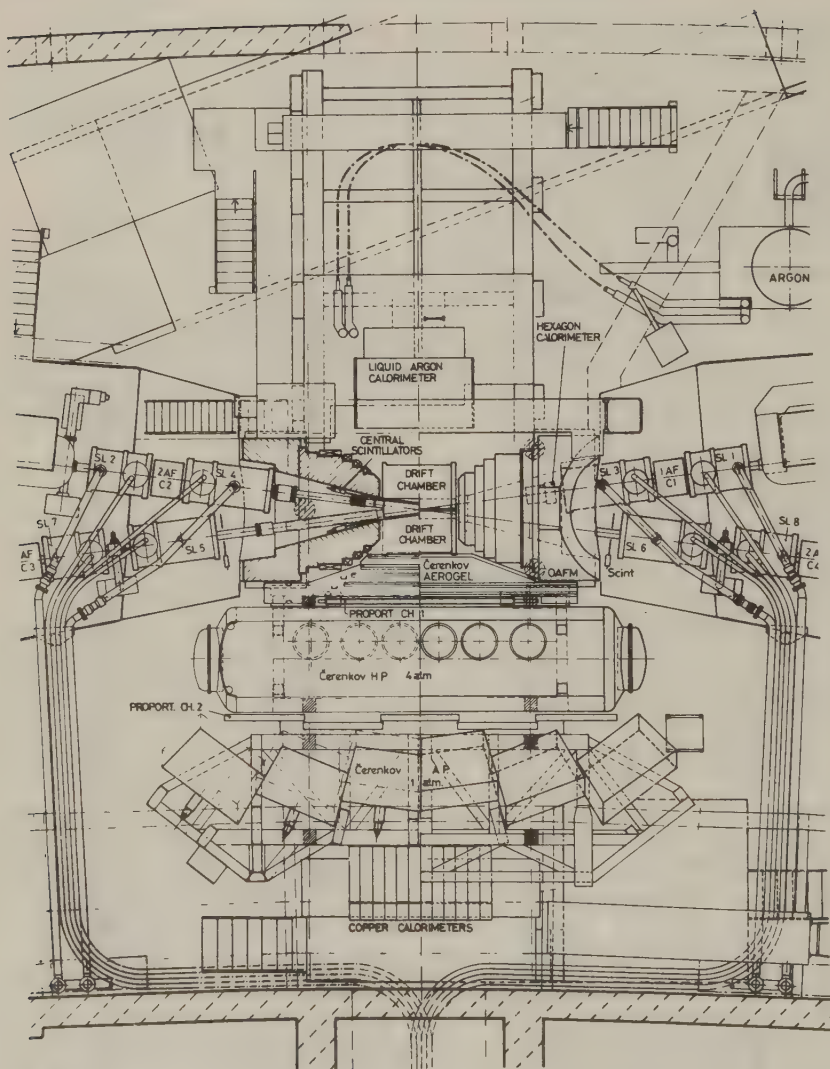


Fig. 2. Top view and horizontal section through the AFS (1981) configuration). It also shows the position of the eight superconducting quadrupoles (SL1 to SL8) of the newly operational low- β high-luminosity insertion.

2.3. Particle identification

Three threshold Cherenkov counters provide identification of relativistic particles over the solid angle of 1 sr (see figs. 1 and 2). The first counter contains a radiator

of silica aerogel [6] with a refractive index of $n = 1.05$; the second is a high pressure counter (HPC) filled with Freon-12 at 4 atm with a refractive index of $n = 1.004$; the third counter is operated, again with Freon-12, at atmospheric pressure ($n = 1.001$, APC). Multiwire pro-

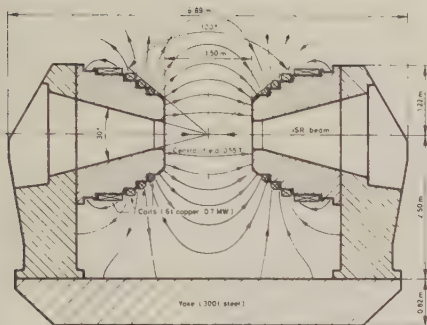


Fig. 3. Vertical cross-section through the open axial field magnet. The magnetic field lines show the direction and level of the field useful for momentum analysis and also the level of "stray field" in the external detectors.

portional chambers (MWPCs) with bidimensional read-out are mounted between the Cherenkov counters and used for triggering and tracking. The counters provide unambiguous identification from 2 to 12 GeV/c.

The relatively high multiplicity of high- P_T events determines the granularity of these counters. The aerogel Cherenkov is subdivided into 20 optical cells, four layers deep, the HPC into 12 and the APC into 18 cells.

Light from the aerogel blocks is projected onto thin wavelength shifters (WLSs); the shifted light is then guided through ~ 2 m long lucite light-guides to low stray field regions, where photomultiplier (PM) operation is relatively easy. Mirror systems are used for both gas Cherenkovs for light collection. Spherical mirrors (typically ~ 2 m² surface) focus the light onto flat mirrors, which are viewed by 5 in. PMs at the end of

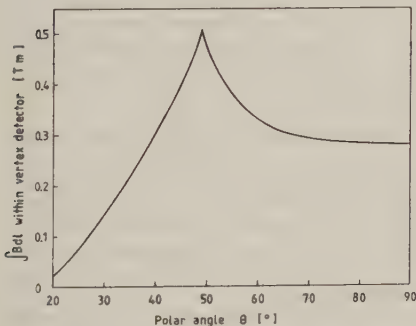


Fig. 4. The magnetic field component transverse to the trajectory of a particle from the vertex, integrated over the radial dimensions of the vertex detector (59 cm) as a function of polar angle (at a nominal power level of 700 kW).

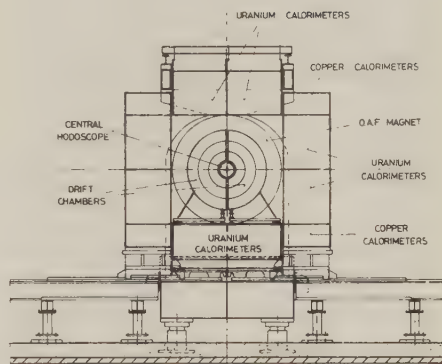


Fig. 5. Cross-section through the AFS showing the drift chamber surrounded by the 2π hadron calorimeter. This layout of the detector is planned for 1982.

Winston cones. Each cell of the HPC is viewed by two such Winston cone-PM combinations to achieve uniform efficiency for all particles originating from the ~ 60 cm long ISR interaction region. The design goals – uniform and good light collection inside a cell and relative to other cells – have been achieved as verified in extensive beam tests. For the HPC we measure, on an average, 25 photoelectrons for relativistic particles and 15 for the APC. An indication of the performance in the ISR is shown in fig. 6. A clear separation between pions and heavier hadrons is achieved, although no attempt has been made to remove background from δ electrons and γ conversions.

2.4. The hadron calorimeter

2.4.1. Principal considerations

While there are compelling physics reasons for using hadron calorimeters in colliding beam experiments, lack of adequate instrumental techniques has so far prevented their use. Only in recent years have calorimetry techniques been studied well enough [7], and suitable read-out techniques developed for sampling calorimeters [8]. Effective use of calorimeters at hadron colliders is particularly difficult for the following two reasons:

1) Invariant cross-sections fall steeply as a function of the transverse momentum, typically as P_T^{-9} ; measured spectra are smeared by the instrumental resolution and may therefore be grossly distorted (see fig. 7). Energy resolution is at a premium!

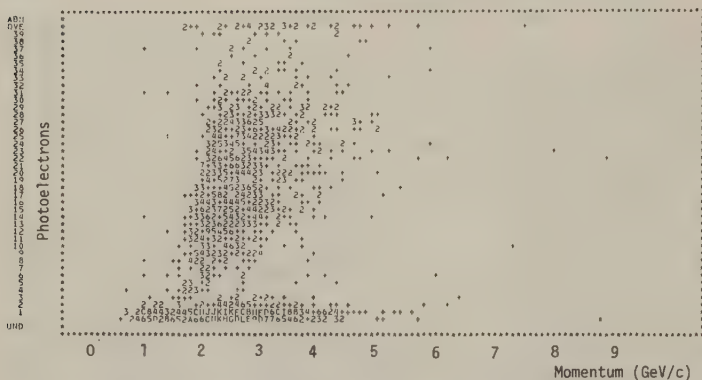


Fig. 6. The ISR performance of HPC, showing the number of photoelectrons as a function of particle momentum. The band of pions is clearly separated from the heavier hadrons.

2) At hadron colliders the calorimeters serve the additional, equally important role of very effective and highly selective trigger devices. Again, apart from the importance of energy resolution, the unbiased selection of final states is only possible if the calorimeters response is independent of the nature of the incident

particle: a truly democratic response is a necessity!

Both of the above requirements are elegantly optimized with the use of ^{238}U as the absorber plates [7] and we therefore adopted this material.

Another fundamental consideration is the "granularity" of such a detector, i.e. the solid angle covered by any read-out channel. The physics suggests a calorimeter granularity consistent with the measurement of individual particles even in highly collimated jets. This imposes a relation between the average absorption length (and hence the transverse dimensions of a hadron shower) and the average separation between the particles at the entrance face of the calorimeter. The high average density of our calorimeter ($\bar{\lambda}_{\text{absorb}} = 22 \text{ cm}$) and the expected particle density in typical ISR jets of $P_T \approx 10 \text{ GeV}/c$ resulted in the present design: the entrance face of the calorimeter starts radially at a distance of 120 cm; the individual cell has an area of $20 \times 20 \text{ cm}^2$ and resolves $\approx 85\%$ of all particles in a jet.

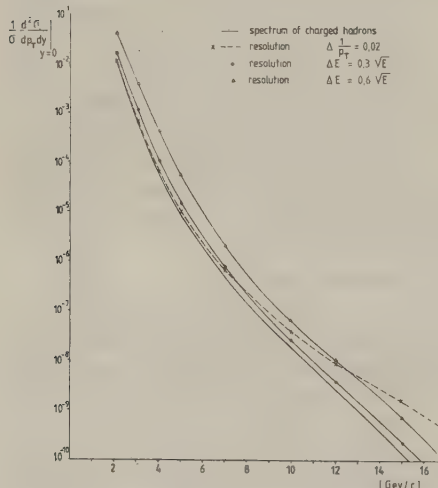


Fig. 7. Effect of detector resolution on a steeply falling particle spectrum, shown for three different resolution functions; $\delta(1/p) = 0.02$ represents the performance of our drift chamber; $\sigma(E)/E = 0.6/\sqrt{E}$ applies typically for a very good non-U hadron calorimeter, while $\sigma(E)/E = 0.3/\sqrt{E}$ is similar to the resolution of our U calorimeter.

2.4.2. Choice of read-out

Two techniques are available for the active read-out of calorimeters [9] which do not affect the intrinsic resolution for electromagnetic showers and which permit a very compact design. The liquid-argon technique, by now matured into a standard method, has proved its reliability and its excellent control of systematic effects at the 1% level. Although we considered it as our first choice, we shied away after initial indications that a surprisingly high premium would have to be paid for the small U plates required for the ion chamber electrodes. We settled for second best by adopting the WLS technique [10,11] for the scintillator read-out.

The method is sketched in fig. 8. As with all light-collection techniques, great care has to be given to:

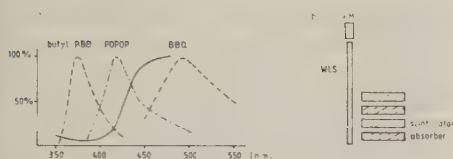


Fig. 8. Spectral response (a) and conceptual arrangement (b) of the scintillator-wavelength shifter system for sampling calorimeter. Light emitted from the scintillator (e.g. butyl PBD or POPOP) enters the wavelength shifter ("BBQ") across an air gap; it is subsequently absorbed and isotropically re-emitted at longer wavelengths.

- 1) minimize non-uniformities in the optical elements;
- 2) minimize dead-space introduced by the WLS bar; it must not have excess response (produced, for example, by Cherenkov light) to direct particle hits;
- 3) provide an adequate calibration for the complete read-out chain.

We arrived at the following optimization [12]. Plastic scintillator* based on PMMA (polymethyl methacrylate) was chosen for cost and mechanical reasons. It was doped with 1% butyl-PBD as the primary scintillating agent and 10% naphthalene was added to improve the light yield (measured to be about 70% of NE102A). No wavelength shifting material was used, as is commonly done ("POPOP"), resulting in a desired, strong absorption of the emission spectrum; we measured for our scintillator an absorption length of $\lambda = 30$ cm, consistent with our cell size. The WLS was again based on PMMA, doped with BBQ. Sufficiently high absorption of the scintillator light, consistent with adequate uniformity ($\pm 5\%$) along the WLS and sufficiently low response to Cherenkov light, was achieved with a 2 mm thick shifter, made from ultraviolet absorbing plexiglas 201**, and doped with 80 mg/l BBQ. Calibration of the complete read-out chain is in general one of the most serious difficulties of this optical technique. We avoided complex auxiliary optical systems by exploiting the natural radioactivity of our plates as the calibration reference. We find that in our stacks the charge measured from one of the PMs of the hadronic part of the calorimeter, during a $10 \mu\text{s}$ ADC gate, corresponds to the signal obtained from a ~ 4 GeV pion. In practice, the U signal of each assembled stack is cross-calibrated with cosmic-ray muons which establish an absolute energy scale. From the modulus constructed to date, we infer that the U radio-activity provides an energy calibration at the 1% level.

2.4.3. Mechanical construction of the calorimeter

The solid angle of 8 sr is covered with 128 identical "stacks" (fig. 9), arranged in four "walls", as shown in fig. 5. The corners of the walls are plugged with smaller stacks made of copper plates to contain approximately 3% of the energy, which would otherwise escape.

Longitudinally the calorimeter is subdivided into two parts. A 5-radiation-length deep electromagnetic (e.m.) part is read out separately from the 3.6-absorption-length deep hadronic section. The final disposition of the plates in a stack reflects the compromise between the requirements for good energy resolution and the wish to minimise the total amount of uranium and the required machining effort. The final optimization resulted in the choice of ten U plates, 2 mm thick for the e.m. part; the hadronic section consists of 38 cells, each composed of two 3 mm U plates followed by one 5 mm Cu plate.

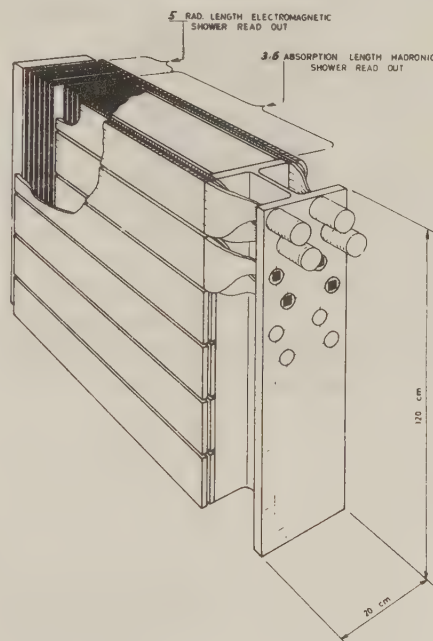


Fig. 9. Sketch of one of 128 calorimeter stacks. Each stack, mechanically homogeneous, is divided optically into 6 cells ($20 \times 20 \text{ cm}^2$), and each cell is read out on both sides and twice along the longitudinal direction. Note that the electromagnetic part uses ten 2 mm thick U plates, whereas the hadronic part is composed of seventy-six 3 mm thick U plates and thirty-eight 5 mm thick Cu plates. Scintillator of 2.5 mm thickness is used throughout. Each stack weighs about 2 t.

* Manufactured by Altulor S.A., Paris, France.

** Manufactured by Rohm GmbH, Darmstadt, Fed. Rep. Germany.

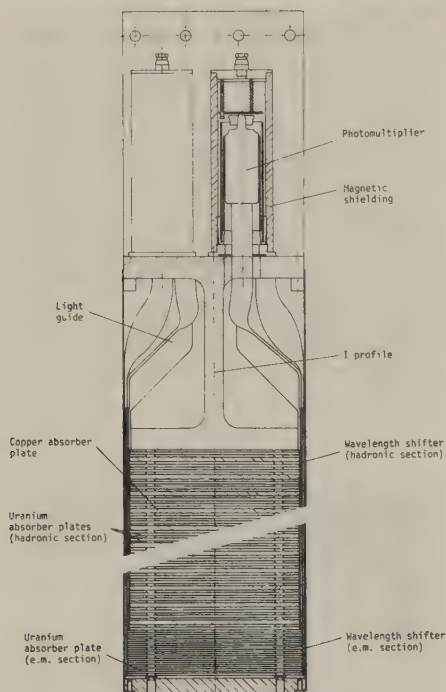


Fig. 10. Horizontal cross-section through a U stack.

In the mechanical construction we aimed – not forgetting ease and simplicity – to minimize dead areas due to structural elements inside the stack. The result is

shown in fig. 10. The plates are tied together with one 10 mm diameter rod; four 10 mm diameter spacers, located in corresponding holes in the corners of the scintillator, and one washer, around the central rod, space the U plate and prevent pressure contact with the scintillators. Constructed in this way, the stacks are self-supporting in four different positions (fig. 5).

Assembly time, including mounting of the WLSs and PMs, requires eight man-days per stack. So far, we have constructed one wall and completion of the calorimeter is scheduled for the summer of 1982.

2.4.4. Performance

Our choice for the light absorption length in the scintillator combined with the read-out arrangement provides excellent position resolution in both transverse directions of a stack. An example is shown in fig. 11, from which one may also judge the optical uniformity of our design. Typically we find for a few GeV/c electrons a spatial resolution of $\sigma_x \approx \sigma_y \approx 10$ mm.

The energy resolution for electrons and hadrons as a function of incident angle into the stack is given in fig. 12. The electron resolution is consistent with the value expected from sampling and photon statistics (300 photoelectrons per GeV). The hadronic resolution reflects the intrinsic resolution of an ideal U calorimeter of

$$\sigma_{\text{intrinsic}}^U/E = 0.2/\sqrt{E} \text{ (GeV)},$$

and the sampling fluctuations, estimated to be

$$\sigma_{\text{sampling}}/E = 0.1 \sqrt{\frac{\Delta E \text{ (MeV) gap}}{E \text{ (GeV)}}} \approx 0.25/\sqrt{E},$$

where ΔE is the energy loss per U cell; $\Delta E \approx 6.5$ MeV. The twofold longitudinal read-out combined with good spacial resolution permits considerable electron/pion discrimination. We find a pion rejection of larger than

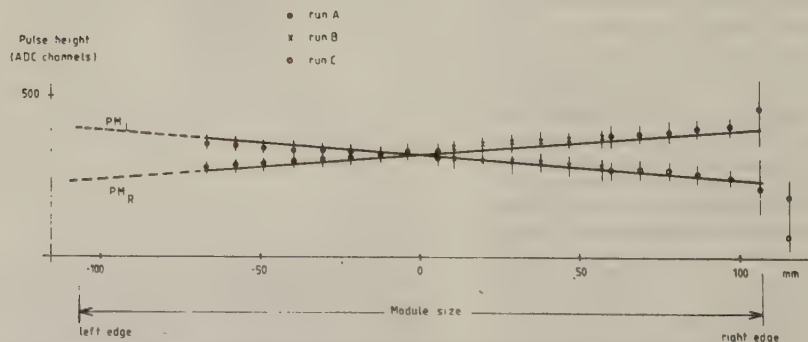


Fig. 11. Mean pulse height as a function of position for 5 GeV/c electrons. The error bars indicate the fwhm of the pulse-height distributions.

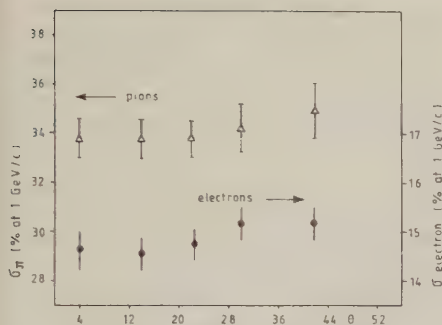


Fig. 12. The normalized energy resolution for electrons and hadrons as a function of incident angle. The angle θ is measured with respect to normal incidence.

50 with $\sim 80\%$ electron acceptance, if complete shower information is available.

3. The AFS trigger system and on-line processors

The AFS is mostly used to study interactions with cross-sections in the microbarn to nanobarn range, frequently in an environment of very high collision rates (without the low- β insertion a typical luminosity of $L = 2 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ implies a particle flux of $> 10^7 \text{ s}^{-1}$ into a 4π detector). Central to efficient study of these relatively "rare" events are trigger and filter schemes, matched in processing power to the primary interaction rate and of sufficient discrimination to permit practical off-line analysis.

On-line processors were developed to evaluate the drift-time information from the central detector, hit patterns from the MWPCs of the Cherenkov arm, and the energy deposition in the calorimeter.

Selection of high- P_T charged particles proceeds through a sequence of increasingly more selective conditions [13]. A rejection of several hundred is obtained in a processing time of less than $1 \mu\text{s}$, by using position information on the drift and MWPC wires [14]. Ultimate rejection of up to about 5000 is based on the drift-time information for sagitta evaluation with a very fast parallel processor, ESOP [13]. Event purity (i.e. the fraction of tracks with P_T above threshold) is $\sim 10\%$; the trigger efficiency at threshold is $\sim 10\%$; and rises to a plateau at $\sim 50\%$. Inclusive spectra up to $P_T = 10 \text{ GeV}/c$ have been recorded in this way.

The trigger processor for the calorimeter is at present being brought into operation. For this purpose the dynode signals from the 3200 individual signal channels are summed over all cells of the same azimuth ("row")

for both the e.m. and hadronic segments. This results in 48 primary e.m. signals, and 48 U and 4 Cu-module hadronic signals. These 100 signals are transmitted via air core cable ($v = 0.95c$) to the counting room for further processing. As indicated in fig. 13, the hadronic sums of adjacent rows are combined, with an overlap of one row. Triggering on energy deposition in such a narrow slice will preferentially select configurations where most of the energy is carried by a single hadron. Similarly, six rows of cells ($\Delta\Omega \approx 1 \text{ sr}$) are combined into "jet sums" to achieve sensitivity for topologies expected to be characteristic of "jet" structure. Again, a geometrical overlap of 67% in the jet sums minimizes edge effects in the azimuthal efficiency of the trigger. The energy sums provide also a measure of the total deposited energy, E_{tot} , which is used as a pre-trigger and strobe for ADCs. A total of 123 fast, linear sums are generated in this way: 48 e.m. single particles (EM), 48 hadronic single particles (SP), 24 jet sums (JET), $E_{\text{tot}}(E)$, E_{tot} e.m. (E_m), $P_{\text{Tot}}(P_T)$. These sums are interrogated by multilevel discriminators (three levels for EM, five SP, four JET, six E , four E_m , three P_T), resulting in 493 signals. Subsequently, the definition of the e.m. single particle trigger is refined by requiring a spatial coincidence of an EM signal with a consistent value of an SP. All the information thus obtained is "multiplicity"-encoded, and transmitted in encoded form onto 33 signal lines. Other detectors (MWPCs and drift chambers), and in particular ESOP filtered tracks at different thresholds, may also be correlated with the calorimeter signals for which an additional 17 encoded lines are provided. Logic decisions on the information pattern present on these 50 signal lines are carried out by an array of high-speed logic units. Each distinct trigger pattern, represented by a unique signal pattern on the 50 lines, is stored in a 50-bit memory. This

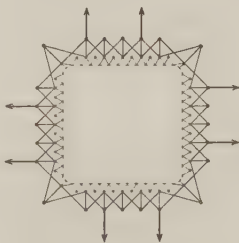


Fig. 13. Schematic diagram of the calorimeter trigger, which uses the information on energy distribution in the transverse plane. A small line segment in the inner square represents the summed up hadronic energy in a "row" of hadronic cells. The lines joining two rows give a "single particle sum", whereas the next level of summing over six rows represents the spatial extension of jets; further summing results in signals representing total energy deposition, E_{tot} .

Table 1
Selection criteria for some special final states ^{a)}.

Experiment	Trigger
1. Identified single-particle inclusive distributions and correlations	BB · ESOP(1) · 2 ⁻ⁿ ; E ⁱ · JET ^j (1) · ESOP(1); E ⁱ · SP ^k (1) · ESOP(1)
2. Identified pairs (pp, KK, ...)	BB · ESOP(2)
3. Jet studies and SP in calorimeter	BB · 2 ⁻ⁿ ; E ⁱ · 2 ^{-m} ; E ^j · JET ^k (1) · 2 ⁻ⁿ ; E ^k · JET ^j (2)
4. Flavour jets	E ⁱ · EM ⁱ (1) · ESOP(1); E ⁱ · EM ⁱ (2) · ESOP(2)
5. Multileptons (≥2)	E ⁱ · E ^j _{em} · EM ^k (2) · ESOP(2)
6. Inclusive electrons	E ⁱ · E ^j _{em} · EM ^k (1) · ESOP(1) · 2 ⁻ⁿ
7. Correlations	E ⁱ · SP ^j (2) · 2 ⁻ⁿ ; E ⁱ · JET ^k (2) · 2 ^{-m}

a) BB stands for "beam-beam" and represents an "unbiased" interaction trigger.

The superscripts *i, j, ...* indicate the minimum discriminator level and the subsequent higher ones.

Numbers in parentheses specify the multiplicity of a trigger condition.

2⁻ⁿ, 2^{-m}, ... give the down-scaling factors for abundant triggers.

arrangement allows parallel decision processing and down-scaling of abundant triggers. A partial list of various representative trigger combinations is provided in table 1.

Data from the drift chamber are recorded in 6888 ADC and 3444 drift-wire recorder channels. Pulse-height information from the full calorimeter will be contained in 3200 ADC channels. Data compaction is achieved on-line by a selective read-out of only those drift wires with a hit, and by using a fast processor to select the corresponding two ADC words; the same processor also groups data into a format, which is optimized for off-line analysis. A similar data compression is foreseen for the calorimeter information, using the ESOP processor. In this way the total number of data words is reduced to ~4000 for an average event, but still may be more than double for high-multiplicity events.

4. The AFS off-line software

For the present AFS experimental configuration the major part of the off-line data analysis consists of assigning drift-chamber digitizings to tracks, and then determining the momentum. (As calorimeter data become available, the analysis of this information will also constitute a significant part of the off-line programs.)

Sorting the digitizings into tracks is a classic problem of pattern recognition. In the transverse (*r, φ*) plane the track trajectory through the chamber is approximately a circle of radius *R*(cm) ≈ 700 *p* (GeV/*c*). Hence for most momenta of interest (≥0.3 GeV/*c*) the radius is much larger than the arc length of the trajectory, which is

≥59 cm for a particle traversing the full chamber. Thus the trajectory can be approximated by:

$$\phi = \phi_0 + \alpha r,$$

i.e. a straight line in *r, φ* coordinates, with a slope related to the particle momentum.

The pattern recognition program proceeds by scanning the *r/φ* plane with a rotating "road", and counting the number of digitizing within the road. A genuine track or track segment will give a large digitizing count. The "left-right" ambiguity is then resolved by requiring that the digitizings be smoothly continuous rather than staggered by twice the sense wire staggering. Reasonable continuity in the *z* coordinate, derived from charge division, is also required at this stage. Finally track segments found within different roads are merged to form the full track. This pattern recognition program takes typically 2 s of IBM 168 time for an event of charged multiplicity 10.

The track digitizings are then passed to the momentum determination program. The procedure used is fairly standard. The time coordinate is eliminated from the equation of motion, resulting in expressions for $d^2(r\phi)/dr^2$ and d^2z/dr^2 . The trajectory is interpolated between the measurement points as a polynomial, so that the integration can be done exactly – the "spline" method. The program then determines the main vertex and secondary (decay) vertices from the fitted tracks. The pulse-height information at the ends of each sense wire, which provides the *z* coordinate, is also a measure of the energy loss, *dE/dx*. Given the number of *dE/dx* measurements, particle identification in the "1/β²" region is readily achieved.

It should be stressed that to obtain the best resolution from the chamber, careful studies must be made of topics like:

- 1) variation of the drift velocity over the drift region;
- 2) pulse-height dependent shifting of the measured time ("slewing");
- 3) cross-talk, etc.

The final program in the present chain studies the tracks going into the Cherenkov arm (see fig. 1). This involves extrapolating the tracks through the various Cherenkov counters and proportional chambers, and identifying the particle. The Cherenkov counters give $\pi/K/p$ separation over the 2–12 GeV/c range.

This large and complex off-line program chain is maintained on four different types of machine (IBM, NORD, UNIVAC, CDC) using the PATCHY system [15].

5. Status and prospects

During 1981 emphasis has been placed on the measurement of inclusive distributions of high- P_T hadrons. The year at the ISR was marked by the advent of proton-antiproton collisions, with exciting prospects for a number of very topical comparative studies. Physics with the calorimeter will finally begin this year, and subsequent years will see full exploitation of the unique experimental possibilities provided by the 2π calorimeter.

Is something missing from this splendid array of instruments? While clearly a substantial list of interesting detectors could be imagined, one notes in particular the lack of detection facilities for rapidities $|y| > 1.3$. It has been suggested [16] to equip the magnet poles with a fine array of proportional wires, thus extending the calorimeter coverage over two more units of rapidity. Preliminary engineering feasibility studies and test results [17] are encouraging. Recent physics results also remind us of the spatial coarseness of the e.m. part of the calorimeter: direct photons have been discovered at the ISR, and there is even an indication for direct γ pair production, yet we cannot detect such events with the U calorimeter: J/ψ 's and perhaps T 's are produced predominantly via the excited $q\bar{q}$ states and subsequent de-excitation via γ emission. Although 10^9 $c\bar{c}$ systems and perhaps 10^6 $b\bar{b}$ systems are being produced daily at the ISR, we are blind to such transitions. Soft and hard electrons of varied origins abound, but we have yet to paint a coherent picture and relate it to the underlying constituent dynamics. The list could be prolonged, but

all these phenomena could be studied if our present calorimeter were to receive a more fine-grained layer of e.m. shower detection. We are pursuing a variety of options to ensure the uniqueness of the instruments and hence its physics potential even beyond the time when we have stopped observing proton-proton collisions in the CERN ISR.

We are most grateful to the CERN management, who have supported the AFS project with foresight and conviction since its inception.

Our staff at the CERN EP, EE, DD, and ISR Divisions and at the collaborating institutions have worked with competence, dedication, and enthusiasm to provide us with a unique tool for studying high-energy collisions and we thank them for their contributions to the success of the apparatus.

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A COMPARISON OF HADRON PRODUCTION IN $p\bar{p}$ AND pp COLLISIONS IN THE CENTRAL REGION AT $\sqrt{s} = 53 \text{ GeV}$

The Axial Field Spectrometer Collaboration

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ABSTRACT

We have studied the inclusive production of the hadrons $\pi^\pm$, $K^\pm$, p , $\bar{p}$, Λ , $\bar{\Lambda}$, ρ , f , K^{*0} , $\bar{K}^{*0}$, and ϕ in the central region at the ISR, $\sqrt{s} = 53 \text{ GeV}$, in both pp and $p\bar{p}$ collisions. Differences are observed only for $K^\pm$, p , and $\bar{p}$ production. We then study also correlations between low- p_T pp and $p\bar{p}$ pairs in the two types of collisions, separating the contribution from baryon pair production and from the incident particles (stopping protons). We observe a positive correlation between two stopping protons; between the production of two pairs, and between a stopping proton and a pair production, there are negative correlations.

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1. INTRODUCTION

In April 1981 the first $p\bar{p}$ colliding beam run took place in the ISR, providing a unique facility for making comparisons between $p\bar{p}$ and pp collisions at very high energy. The difference in the total cross-sections [1] is small, $\sigma_T(p\bar{p}) - \sigma_T(pp) \approx 1$ mb at $\sqrt{s} = 53$ GeV, and the global features of inelastic $p\bar{p}$ collisions are very similar to those already well known for pp collisions. We have previously compared single-particle production in the central region for $p_T < 1.5$ GeV/c [2], finding differences in the p_T and y distributions of identified $p(\bar{p})$, compared [3] event features as a function of total charged transverse energy E_T^c up to $E_T^c = 12$ GeV, and compared [4] unidentified hadron (and hadron-pair) spectra up to $p_T \approx 6$ GeV/c. In the latter studies [3,4] no significant differences between $p\bar{p}$ and pp collisions were found.

In this paper we report on a systematic comparison of central particle production, including resonances (ρ , f , K^* , ϕ) and baryons (p , $\bar{p}$, Λ , $\bar{\Lambda}$), extending a previous study [5] with only pp collisions. Channels which may be sensitive to $q\bar{q}$ annihilation (e.g. ϕ production) are of particular interest to compare in $p\bar{p}$ and pp ; in lower energy pp collisions $q\bar{q}$ annihilation does not contribute significantly to ϕ production [6]. From baryon/antibaryon distributions one obtains further information relevant to the mechanism of particle production. It is known from previous experiments [7,8] that a sizeable fraction of the low- p_T protons close to $y = 0$ in pp collisions does not come from baryon-antibaryon pair creation but is directly associated with the incoming baryon number. To the degree that such distinction makes sense, a comparison of p and $\bar{p}$ production in pp and $p\bar{p}$ collisions makes it possible, in principle, to disentangle these two sources of protons in the central region. We measure the amplitude of these components and investigate whether there is evidence for a positive correlation between protons originating from the fragmentation of the two beam particles. It has been suggested [9] that a positive correlation may exist, where the two protons "stop" each other, losing most of their energy through the emission of mesons.

2. APPARATUS AND DATA ANALYSIS

The experiment was performed with the Axial Field Spectrometer [10] (AFS) at the CERN Intersecting Storage Rings (ISR). For the present investigation only the cylindrical drift chamber, shown in fig. 1 of ref. [5], and scintillator hodoscopes were used. The drift chamber is situated in an axially symmetric magnetic field of 0.5 T. A cylindrical scintillator hodoscope is placed between the vacuum chamber and the drift chamber. It consists of 44 strips, each covering 8° in azimuth with a length of 0.6 m at a radius $r = 0.18$ m.

The drift chamber and its performance are described in detail elsewhere [10]. It is 1.4 m long, and extends radially from 0.20 to 0.80 m. It is segmented azimuthally in 4° sectors, each with 42 resistive sense wires, which provide the coordinates in the transverse plane from drift-time and the position along the sense wire from a measurement of the pulse-heights recorded at both ends. Particles are identified using the information on the ionization from the drift chamber. The truncated mean pulse-height for a track was defined as the mean value of the lower 70% of the individual pulse-heights and was used as a measure of the ionization. Figure 2 of ref. [5] shows the truncated mean pulse-height versus track momentum for negative particles. Particles are identified in regions where the contamination of other particles is low (5–10%), i.e. kaons to 600 MeV/c and protons (antiprotons) to 1.1 GeV/c.

The resolution in the drift chamber is $230 \mu\text{m}$ (r.m.s.) perpendicular to the wires and 1.5 cm (r.m.s.) along the wires. The resulting momentum resolution for full-length tracks is found to be $\Delta p/p \approx \sqrt{(0.025 p)^2 + (0.01)^2}$ (p in GeV/c), where the first term comes from measurement errors, and the second from multiple scattering in the chamber gas and wires. For dE/dx measurements the truncated mean pulse-height for minimum ionizing tracks has $\sigma_{\text{rms}}/\text{mean} = 11\%$ for > 30 pulse-height measurements.

Two sets of scintillators were placed around the downstream beam pipes to record the luminosity and for use in the trigger. The range of scattering angles covered by these counters was $1.2^\circ < \theta < 6^\circ$. The trigger used was defined by a coincidence between these downstream beam counters. Therefore, all distributions shown are for events with at least one charged particle with $1.2^\circ < \theta < 6^\circ$ to each beam axis. Diffractive events are essentially excluded by this trigger. The cross-section detected by this trigger was 21 mb for both the pp and p $\bar{p}$ runs. The data in this paper were taken at $\sqrt{s} = 53$ GeV.

A total of 172,000 p $\bar{p}$ and a similar number of pp events were reconstructed using the pattern recognition and geometry programs [11] developed for the AFS.

Events were accepted for the analysis if they either had a vertex in a fiducial box around the centre of the interaction diamond or at least one accepted track passing this box. Events that were accepted without having a reconstructed primary vertex had a very low multiplicity of accepted tracks, 90% being one-prong events.

The cuts imposed on the tracks were chosen to ensure that accepted tracks passed close to a reconstructed primary vertex or within the interaction diamond, and that the momentum-measurement error was small.

The acceptance for charged particles in the c.m.s. was found to be uniform in rapidity for $|y| \lesssim 0.8$ and in azimuth in the regions $|\phi| < 80^\circ$ and $110^\circ < \phi < 250^\circ$, i.e. within a total azimuthal range of $\Delta\phi = 300^\circ$. The acceptance was identical within a few per cent for both charges and both polarities of the magnetic field. In p $\bar{p}$ collisions the $\bar{p}$ beam has negative rapidity y .

3. SINGLE-PARTICLE PRODUCTION

The p_T distributions of unidentified charged particles in pp and p $\bar{p}$ collisions are shown in fig. 1, normalized to the trigger cross-sections. The p_T distributions are seen to be identical within errors for p_T up to 5 GeV/c. This confirms our previous comparison [4], which was based on a single-particle trigger in the AFS calorimeter.

Also shown in fig. 1 is the inclusive spectrum at $y = 0$, measured by the British-Scandinavian Collaboration [7]. The shape, as well as the normalization, is seen to agree well with the present measurements for p_T up to 5 GeV/c. This indicates that the non-diffractive events selected in the present study have a p_T distribution similar to the inclusive distribution in the region studied, and that the acceptance for $p_T > 0.2$ GeV/c is close to 100%. For $p_T < 0.2$ GeV/c our acceptance is less than 1.0 (0.8 for $0.1 < p_T < 0.2$ GeV/c and 0.25 for $p_T < 0.1$ GeV/c), as shown by the comparison with the inclusive spectrum, assuming that the agreement between the spectra extends also to this low- p_T region. No correction has been applied to this inefficiency in the following.

The observed charged multiplicity distributions in $|y| < 0.8$, $\Delta\phi = 300^\circ$ are shown in fig. 2 for pp and p $\bar{p}$ collisions. We have not attempted to correct for decays, e.g. K_S^0 . No significant differences are seen. In particular no sign is seen of a high multiplicity annihilation component in the p $\bar{p}$ data when compared with the pp data. The error in the observed multiplicity due to the inefficiency at low p_T is estimated to be around 10%.

Figure 3 shows the ratio of identified charged pions, with $p < 500$ MeV/c, in p $\bar{p}$ and pp collisions versus rapidity. No rapidity dependence of these ratios is observed, within the y -range covered.

The ratios of p $\bar{p}$ to pp production for kaons and protons (p, $\bar{p}$) as a function of p_T and rapidity are shown in figs. 4 and 5. Table 1 gives the overall ratios. They are all in agreement with our previous results at $\sqrt{s} = 63$ GeV [2], but the statistics are now four times larger. The present data do not show any significant p_T dependence of the ratios, although our previous results suggested such a dependence for p and $\bar{p}$ production. We again observe a significant y -dependence of the ratio of $\bar{p}$ and p production, the $\bar{p}(p)$ being

relatively more (less) abundant as y becomes increasingly negative, i.e. toward the $\bar{p}$ fragmentation region. The observation of more $\bar{p}$, even at $y \approx +0.6$ (in the p fragmentation region), in $p\bar{p}$ than in pp demonstrates that the influence of the baryon number of an incident particle can extend across the central region into the backward hemisphere, as discussed in ref. [2]. Our earlier results on these ratios [2] have been interpreted [12] as evidence for "held back" valence quarks, a feature of the dual parton model.

4. RESONANCE PRODUCTION

From mass plots of pairs of charged pions, kaons, protons and antiprotons, signals for ρ , f , K^* , $\bar{K}^*$, ϕ , Λ , and $\bar{\Lambda}$ could be extracted. Invariant masses of $\pi^+\pi^-$, $K^+\pi^-$, K^+K^- , $p\pi^-$, and $\bar{p}\pi^+$ were formed using dE/dx identified kaons, protons, and antiprotons, and calling any other charged particle a pion. For the kaon sample used in $K^+\pi^-$ we estimate the contamination to be 5–10%. To increase the statistics for K^+K^- , $p\pi^-$, and $\bar{p}\pi^+$ the requirements on the kaons, protons, and antiprotons were relaxed. This does increase the contamination of the identified particles, but as the ϕ , Λ , and $\bar{\Lambda}$ resonances are very narrow this does not appreciably affect the signal.

The uncorrelated backgrounds for the $\pi^+\pi^-$, $K^+\pi^-$, $p\pi^-$, and $\bar{p}\pi^+$ pairs were estimated by combining tracks from different events. The background-subtracted spectra for these channels and the raw spectra for K^+K^- are shown in fig. 6 for $p\bar{p}$ collisions. The corresponding spectra for pp collisions are essentially identical, not showing any significant differences. Clear signals of the ρ , K^* , $\bar{K}^*$, ϕ , Λ , and $\bar{\Lambda}$ resonances are seen. A structure is seen in $\pi^+\pi^-$ at 1300 MeV which we interpret as the $f(1270)$. Only those Λ and $\bar{\Lambda}$ which decay close to the primary vertex, so that a secondary vertex is not resolved, appear in the $p\pi$ plots. The lines represent the fits to the sum of the resonance peak and the correlated background, used to extract the amount of resonance production. For the ρ we have used a function of the form $(x - a)^b \exp(-cx)$ to describe the remaining correlated background. The background below the f is described by an exponential. The ρ and f peaks are described by a relativistic Breit-Wigner distribution. The background below K^* is well described by a straight line. A relativistic Breit-Wigner distribution was used to fit the K^* peak. The masses of ρ , f , and K^* were allowed to vary in the fits, whereas the widths were kept fixed. The mass distribution in the ϕ , Λ , and $\bar{\Lambda}$ regions were fit to a straight-line background plus a Gaussian with varying mass and width. Table 2 shows the fitted numbers. The table also includes results of a fit to the K^0 peak, seen in the $\pi^+\pi^-$ mass distribution, which is taken as a measure of our mass resolution (again, only promptly decaying K_S^0 are included). The ratios of ρ , f , K^* , $\bar{K}^*$, ϕ , Λ , and $\bar{\Lambda}$ production in $p\bar{p}/pp$ are within errors all consistent with being equal to 1.0.

Figures 7 and 8 show the ratios of the inclusive cross-sections of ρ , K^* , $\bar{K}^*$, and ϕ , in $p\bar{p}$ and pp collisions, as functions of p_T and rapidity. No clear differences are seen between pp and $p\bar{p}$ collisions, within the errors, i.e. the measured cross-sections from pp collisions can be used to describe the yields in $p\bar{p}$ collisions as well, for the range studied. Thus the annihilation channel is not found to be a significant source of ρ , f , K^* , $\bar{K}^*$, ϕ , Λ , and $\bar{\Lambda}$ in $p\bar{p}$ at the present level of accuracy.

Other measurements at lower energies [6] have found that in pp collisions strange quark fusion contributes significantly to ϕ production. A signature of strange quark fusion should be an associated production of kaons in events with a ϕ . Figure 9 shows the mean number of extra kaons as a function of the invariant mass of K^+K^- , and there is no significant enhancement at the ϕ mass.

5. STOPPING PROTONS

It has been known for some time [8], from the observation that the ratio $p/\bar{p}$ exceeds 1.0 at $y = 0$ in pp collisions at the ISR, that an incident proton can lose all its kinetic energy in particle production (stopped protons). There is also the baryon pair-production process which one would expect to give rise to equal

numbers of p and $\bar{p}$ in the central region. Measurements of single and double baryon production, in pp and $p\bar{p}$ collisions, can shed light on these processes. For example:

- i) when one proton (in pp) stops, is there an enhanced probability that the other also stops?
- ii) Is baryon pair production identical in pp and $p\bar{p}$ collisions?
- iii) If one pair is produced, is the probability of another pair being produced enhanced or depressed?

We have measured the probability in our event sample of observing an identified p or $\bar{p}$, or two such particles, in the central region described above. The acceptance is not simple, owing to identification ranges from dE/dx , but is identical for p and $\bar{p}$, and for pp and $p\bar{p}$ collisions, so comparisons are meaningful.

Table 3 lists the 10 processes measured, where we give the fraction of the event sample for each class. If we consider two origins or classes of central baryons, those from pair production with a probability a , and those from beam stopping—the probability of each beam particle stopping (in our acceptance region) being b —then we can compute the expected probabilities of these processes.

In addition we define:

- d = a possible correlation between pair creation and a stopping proton ($d = 1$ if the processes are independent).
- e = the probability that if a p (or $\bar{p}$) from pair creation is detected, its partner will also be detected, which must be the same in pp and $p\bar{p}$.
- f = a possible correlation between detecting one stopped proton and the other beam particle as a stopped proton (antiproton). No enhancement would give $f = 1$.
- g = a possible correlation between one pair production and a further pair production [$g > 1$ ($g < 1$) if the number of pairs produced has a multiplicity distribution wider (narrower) than a Poisson distribution].

We can now calculate the expected probabilities for the 10 processes, as given by the formulae in table 3. We are assuming that the parameters d , e , f , and g are identical in pp and $p\bar{p}$ collisions.

From the single-particle production processes A, B, C, and D we find, from a least-squares fit to the four processes, $a = (2.36 \pm 0.04) \times 10^{-2}$ and $b = (0.74 \pm 0.03) \times 10^{-2}$, with $\chi^2/\text{d.o.f.} = 2.6/2$. We thus find that a good fit results from assuming a and b to be identical in pp and $p\bar{p}$ collisions, and we shall continue to make that assumption in the following, although we cannot exclude the possibility that one rises and the other falls with the sum, $a + b$, approximately constant. Pair creation is the larger source of central p and $\bar{p}$, a/b being ~ 3 . Using these values for a and b we can determine the four parameters d , e , f , and g by a least-squares fit to the six processes E to J. Processes H and J are identical by C-conjugation; they differ by 2σ which is the major contributor to the $\chi^2/\text{d.o.f.} = 2.8/1$. Our assumption that d , e , f , and g are identical in pp and $p\bar{p}$ collisions is justified by the fit. The values for the fitted parameters are given in table 4. The errors are statistical, plus a possible systematic error resulting from the different absorption probability of p and $\bar{p}$ in the vacuum pipe and detector material.

All four correlation terms are significantly different from 1.0. The parameter $d = 0.16 \pm 0.22$ is lower than 1.0, and thus the observation of a stopping proton decreases the probability of observing a pair creation in this rapidity region. The parameter $e = 0.068^{+0.012}_{-0.008}$ simply means that if we observe a pair-created p or $\bar{p}$, the probability that we observe its partner as an identified $\bar{p}$ or p is $\sim 7\%$, given mainly by acceptance. The parameter $f = 3.0 \pm 1.4$ shows an increased probability of observing a second stopped beam particle, given one. From an estimate of our acceptance for identified p and $\bar{p}$, we find that the cross-section for the process where both beam particles appear in the region $|y| < 0.8$, $0.1 < p_T < 1.2 \text{ GeV}/c$ is $60 \pm 30 \mu\text{b}$ [†]. The parameter $g = 0.31 \pm 0.10$ shows that the observation of a pair creation

[†] The cross-section for stopping both *nucleons* is presumably a factor four higher, as the nucleon may appear equally as p or n . This is of the same order as the $p\bar{p}$ annihilation cross-section, $\sigma_{\text{ann}}(p\bar{p}) - \sigma_{\text{ann}}(pp)$, which may be more than a coincidence. We thank M. Jacob for pointing this out.

decreases the probability of observing a second independent pair creation in the same rapidity region, and thus the distribution of multiplicity of pair-creation processes is narrower than Poisson. It should be stressed that these remarks apply to a limited central interval of rapidity.

Finally, we can fit the data on reactions A, B, C, and D to determine a and b as functions of the detected charged multiplicity in the event. This was motivated by the possibility that stopped protons are correlated with high central multiplicity. The results are shown in fig. 10. There is a weak tendency for b to rise faster than linearly in the multiplicity (with an opposite trend for a), but no strong conclusions on this point can be drawn.

6. CONCLUSIONS

The inclusive p_T distributions of charged particles in the central rapidity range $|y| < 0.8$ in pp and $p\bar{p}$ collisions at $\sqrt{s} = 53$ GeV are found to be similar up to $p_T \approx 5$ GeV/c. We observe small differences in the charged kaon and baryon production.

The production of ρ , f , K^{*0} , $\bar{K}^{*0}$, ϕ , Λ , and $\bar{\Lambda}$ in $p\bar{p}$ interactions has been studied as functions of p_T and rapidity and compared with corresponding pp data. Within errors we do not observe any difference in the production of these particles between pp and $p\bar{p}$ collisions.

Comparisons of single- and double-baryon production have shown several correlation effects: a positive correlation between two "stopping protons", a negative correlation between two pair-creation processes, and a negative correlation between a stopping proton and a pair-creation process.

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Table 1

Ratios of particle production in the central
region in $p\bar{p}$ and pp interaction

Particle type	$n(p\bar{p})/n(pp)$
all ($\pm$)	0.999 ± 0.002
+	0.974 ± 0.003
-	1.026 ± 0.003
$K^+ + K^-$	1.021 ± 0.013
K^-	1.086 ± 0.020
K^+	0.961 ± 0.020
$p + \bar{p}$	1.022 ± 0.016
p	0.84 ± 0.02
$\bar{p}$	1.32 ± 0.03

Table 2

Total ratios of resonance production

Particle	$n_{p\bar{p}}/n_{pp}$	Mass (MeV)		Width (MeV)	
		$p\bar{p}$	pp	$p\bar{p}$	pp
ρ	1.01 ± 0.08	765.6 ± 4.1	766.6 ± 4.8		
K^{*0}	0.84 ± 0.20	886.5 ± 5.2	899.3 ± 5.5		
$\bar{K}^{*0}$	1.05 ± 0.23	896.7 ± 7.1	890.5 ± 5.0		
ϕ	0.86 ± 0.18	1019.9 ± 1.1	1020.9 ± 0.9	13	11
K^0	1.13 ± 0.17	503.3 ± 1.3	502.9 ± 1.4	15	19
Λ	1.19 ± 0.17	1119.8 ± 1.2	1118.9 ± 1.3	20	20
$\bar{\Lambda}$	1.14 ± 0.15	1118.5 ± 1.2	1118.0 ± 1.3	23	22
f	1.01 ± 0.43	1299.0 ± 30.0	1300.0 ± 31.0		

Table 3

Single- and double-baryon production processes measured.
See text for the probability notation.

Symbol	Process	Probability	Measurement
A	$p \rightarrow p \leftarrow p$	$a + 2b$	$(3.80 \pm 0.05) \times 10^{-2}$
B	$p \rightarrow \bar{p} \leftarrow p$	a	$(2.33 \pm 0.04) \times 10^{-2}$
C	$p \rightarrow p \leftarrow \bar{p}$	$a + b$	$(3.15 \pm 0.05) \times 10^{-2}$
D	$p \rightarrow \bar{p} \leftarrow \bar{p}$	$a + b$	$(3.13 \pm 0.05) \times 10^{-2}$
E	$p \rightarrow pp \leftarrow p$	$\frac{1}{2}ga^2 + fb^2 + 2dab$	$(3.10 \pm 0.49) \times 10^{-4}$
F	$p \rightarrow p\bar{p} \leftarrow p$	$\frac{1}{2}ga^2 + ea + 2dab$	$(17.5 \pm 1.2) \times 10^{-4}$
G	$p \rightarrow \bar{p}\bar{p} \leftarrow p$	$\frac{1}{2}ga^2$	$(0.85 \pm 0.26) \times 10^{-4}$
H	$p \rightarrow pp \leftarrow \bar{p}$	$\frac{1}{2}ga^2 + dab$	$(1.58 \pm 0.35) \times 10^{-4}$
I	$p \rightarrow p\bar{p} \leftarrow \bar{p}$	$\frac{1}{2}ga^2 + ea + 2dab + fb^2$	$(18.8 \pm 1.2) \times 10^{-4}$
J	$p \rightarrow \bar{p}\bar{p} \leftarrow \bar{p}$	$\frac{1}{2}ga^2 + dab$	$(0.87 \pm 0.26) \times 10^{-4}$

Table 4

Results of fits to stopping-proton and
pair-creation parameters

Parameter	Fit
a	$(2.36 \pm 0.04) \times 10^{-2}$
b	$(0.74 \pm 0.03) \times 10^{-2}$
d	0.16 ± 0.22
e	$0.068^{+0.012}_{-0.004}$
f	3.0 ± 1.4
g	0.31 ± 0.10

Figure captions

- Fig. 1 The observed p_T distribution of charged particles for $|y| < 0.8$, in pp and $p\bar{p}$ collisions at $\sqrt{s} = 53$ GeV. The line shows the inclusive spectrum $(1/\sigma_{in}) (d\sigma/dydp_T)$ at $y = 0$ from ref. [7].
- Fig. 2 The observed charged particle multiplicity distributions, in $|y| < 0.8, \Delta\phi = 300^\circ$, in pp and $p\bar{p}$ collisions at $\sqrt{s} = 53$ GeV.
- Fig. 3 Ratio of $p\bar{p}$ to pp collisions for the production of π^- and π^+ versus rapidity y , for $p_\perp < 500$ MeV/c. The incident $\bar{p}$ has negative y .
- Fig. 4 Ratio of $p\bar{p}$ to pp collisions for the production of identified K^- and K^+ versus rapidity y and p_T .
- Fig. 5 Ratio of $p\bar{p}$ to pp collisions for the production of identified $\bar{p}$ and p versus rapidity y and p_T .
- Fig. 6 Invariant mass distributions for particle pairs in $p\bar{p}$ collisions, after subtracting an uncorrelated background except for K^+K^- .
- a) $\pi^+\pi^-$, inset shows the region of the $f(1270)$. Combinations/25 MeV.
 - b) $K^+\pi^-$, combinations/20 MeV.
 - c) $K^-\pi^+$, combinations/20 MeV.
 - d) K^+K^- , combinations/5 MeV.
 - e) $p\pi^-$, combinations/5 MeV.
 - f) $\bar{p}\pi^+$, combinations/5 MeV.
- Fig. 7 Ratio of $p\bar{p}$ to pp collisions for the production of (a) ρ^0 , (b) K^{*0} , (c) $\bar{K}^{*0}$, (d) ϕ versus p_T , for $|y| \lesssim 1.0$.
- Fig. 8 Ratio of $p\bar{p}$ to pp collisions for the production of (a) ρ^0 , (b) K^{*0} , (c) $\bar{K}^{*0}$, (d) ϕ versus $|y|$ for $p_T \lesssim 1.2$ GeV/c.
- Fig. 9 Average number of additional $K^\pm$ observed in association with a K^+K^- pair, as a function of the mass of that pair, for $p\bar{p}$ and pp collisions.
- Fig. 10 Values of the parameter a (full circles) and b (squares) versus the observed charged multiplicity.

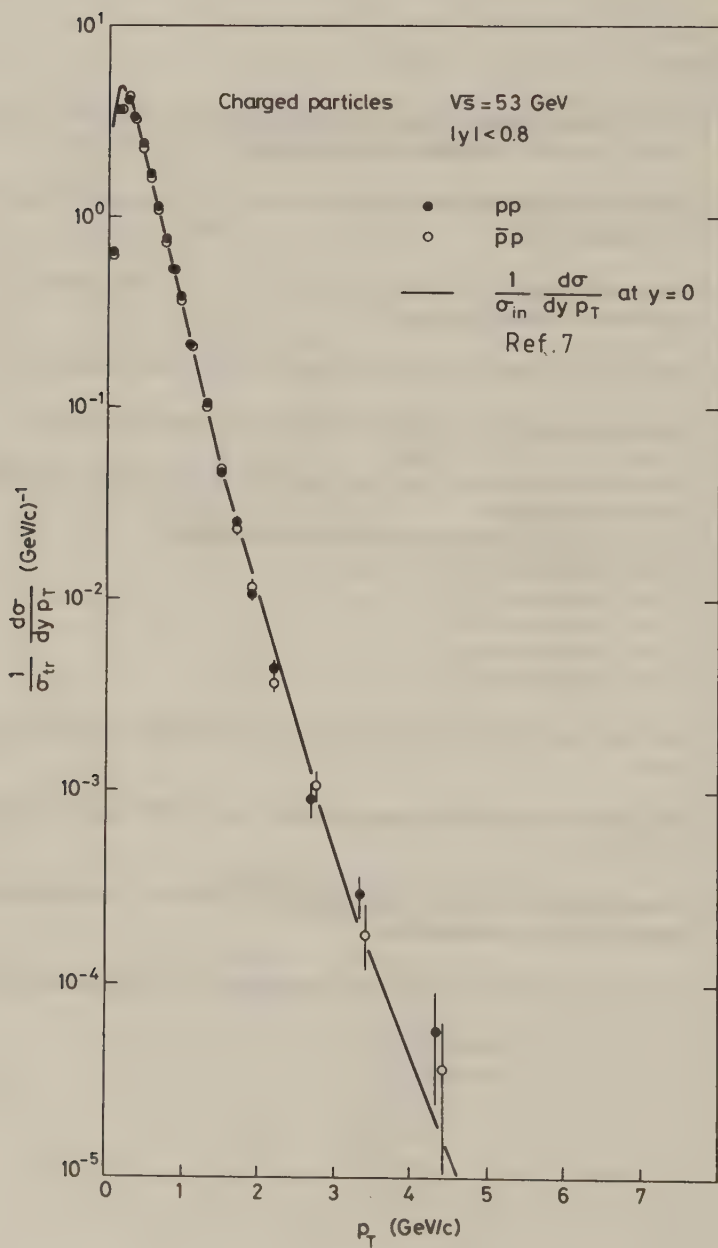


Fig. 1

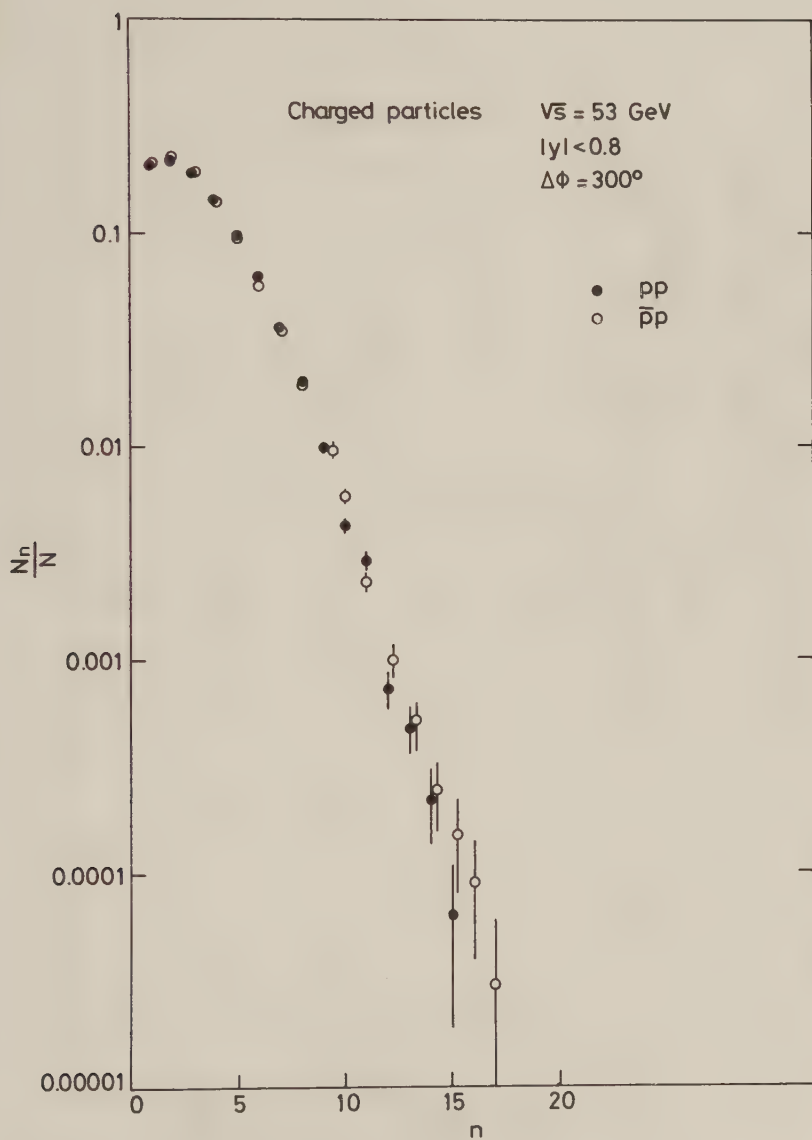


Fig. 2

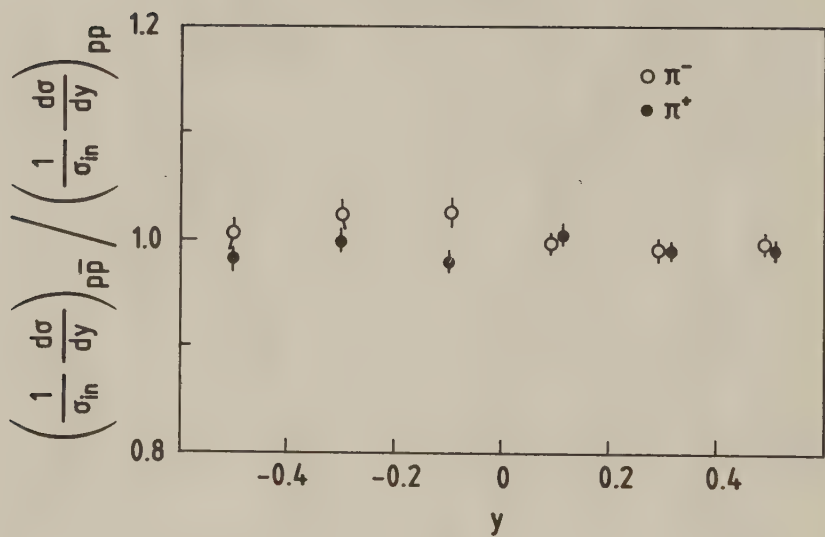


Fig. 3

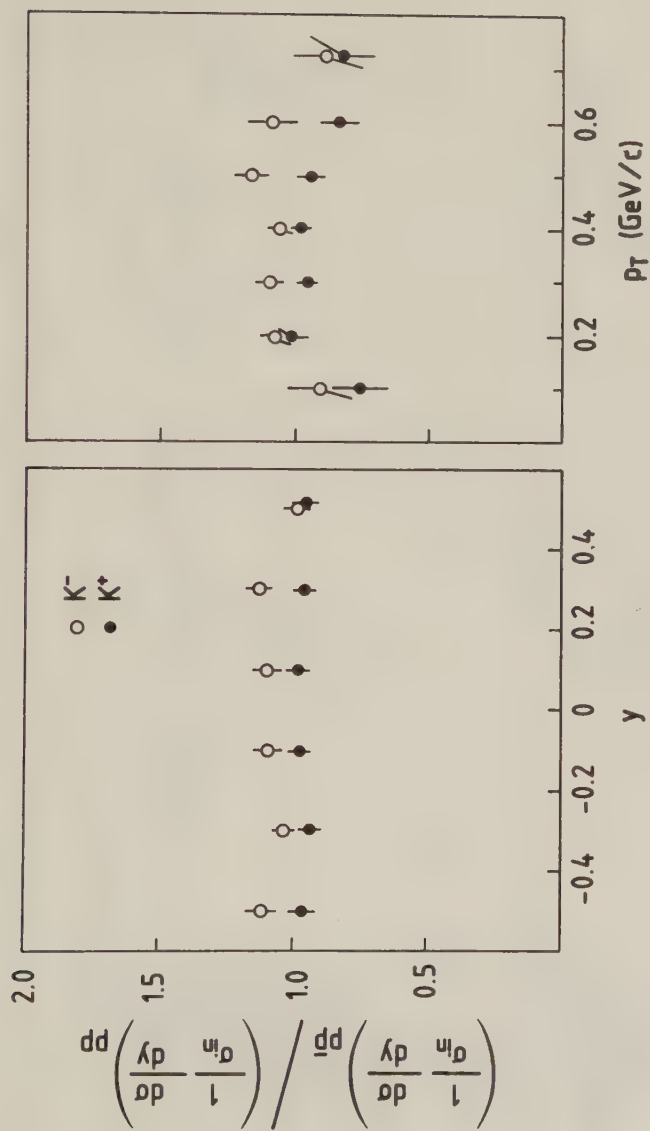


Fig. 4

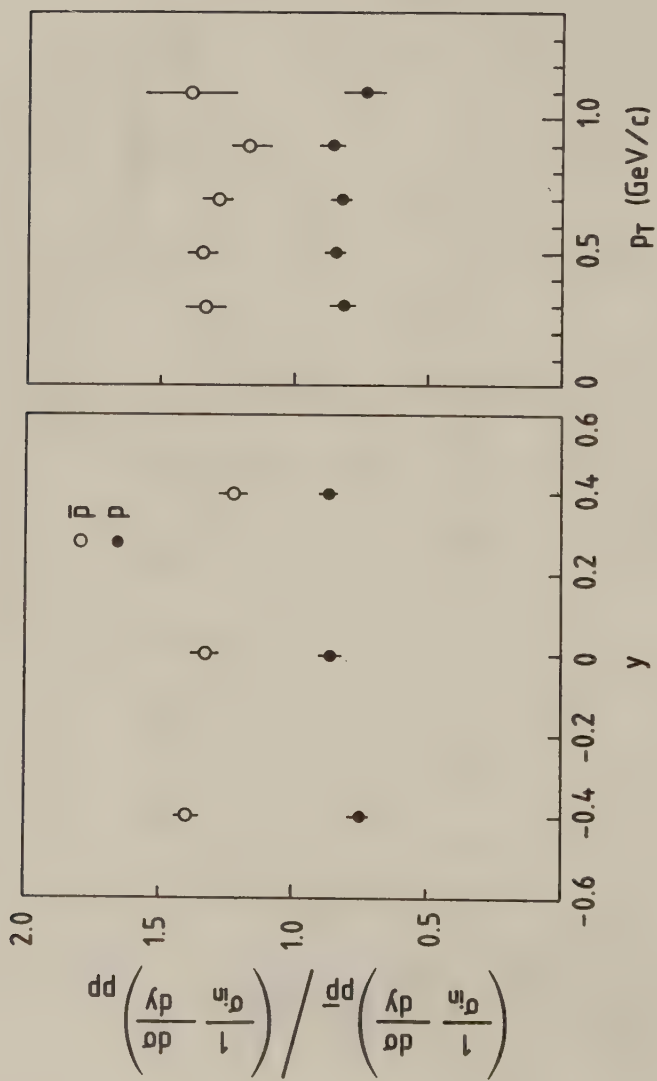


Fig. 5

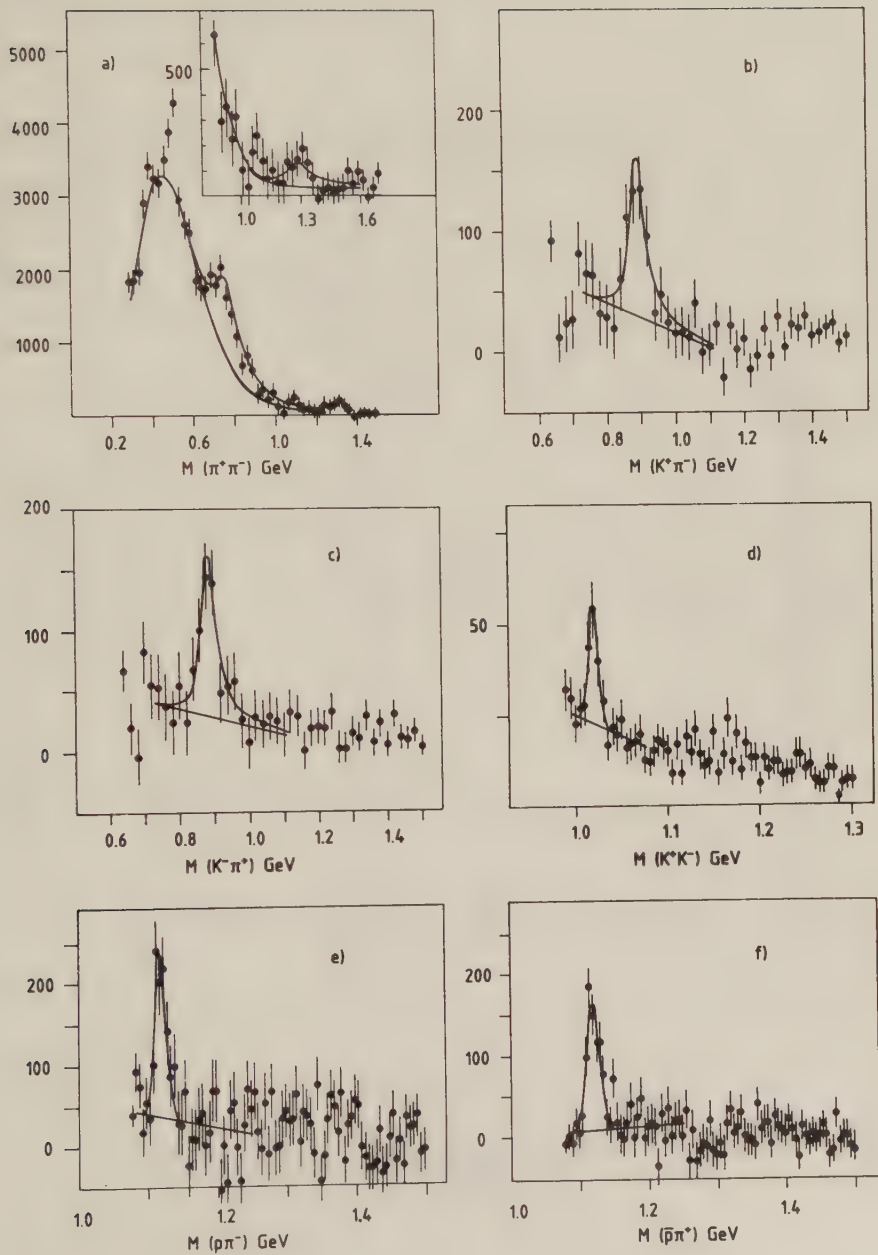


Fig. 6

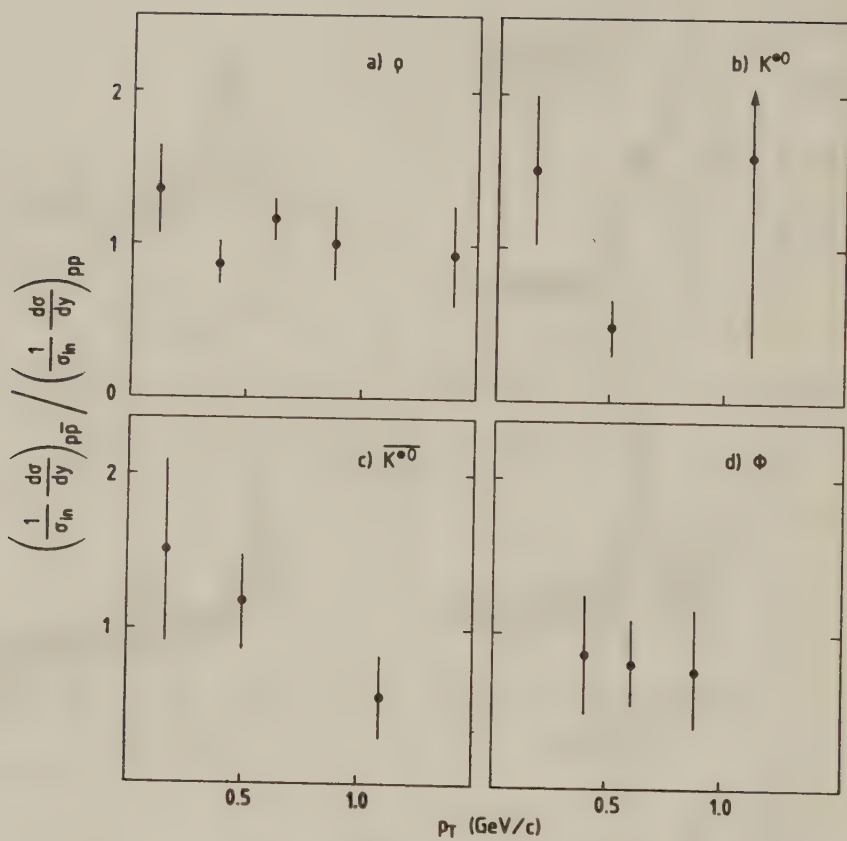


Fig. 7

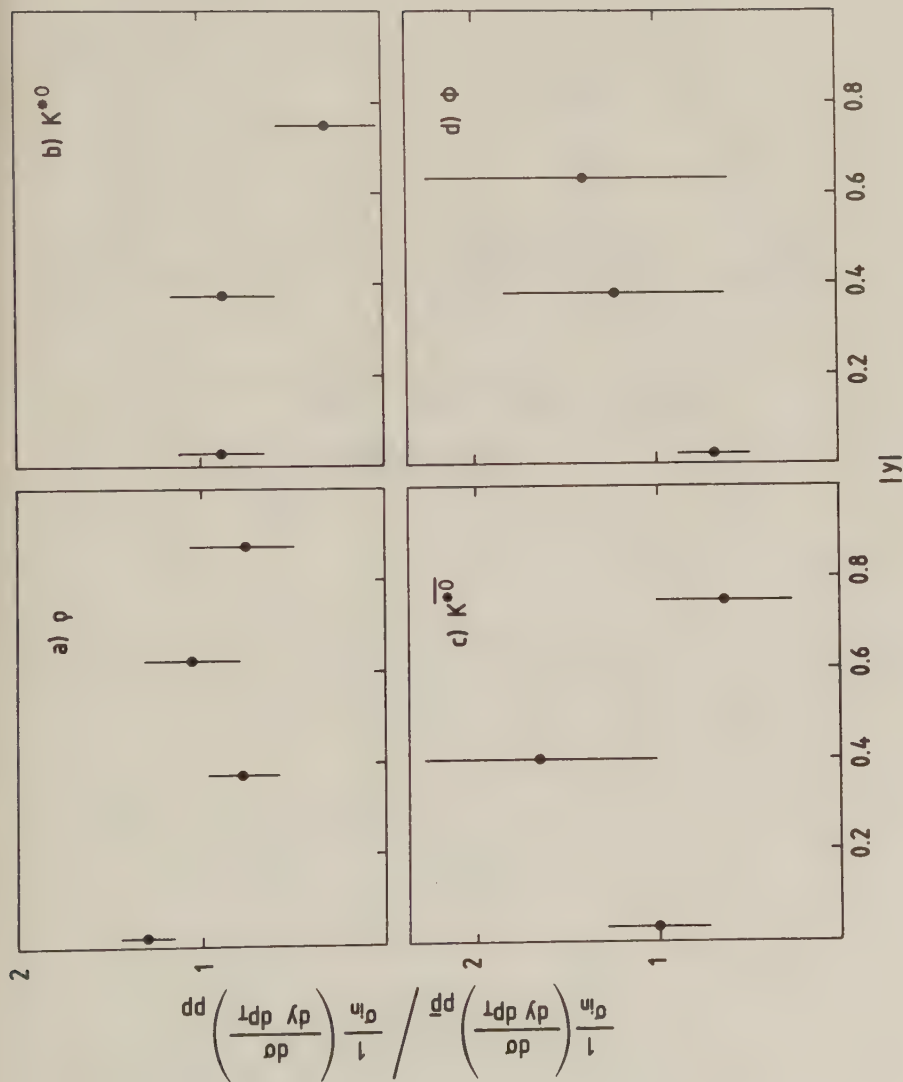


Fig. 8

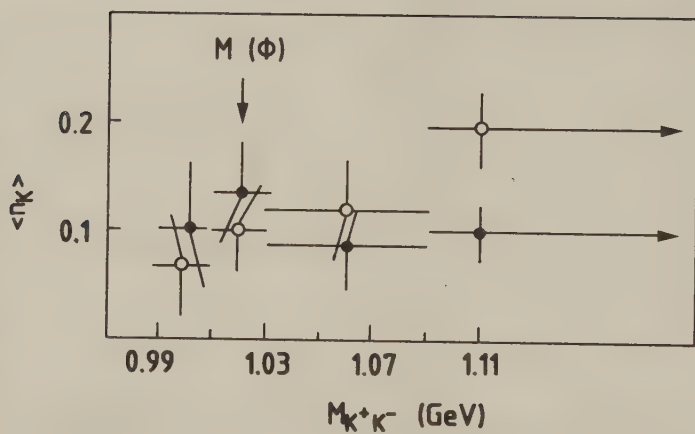


Fig. 9

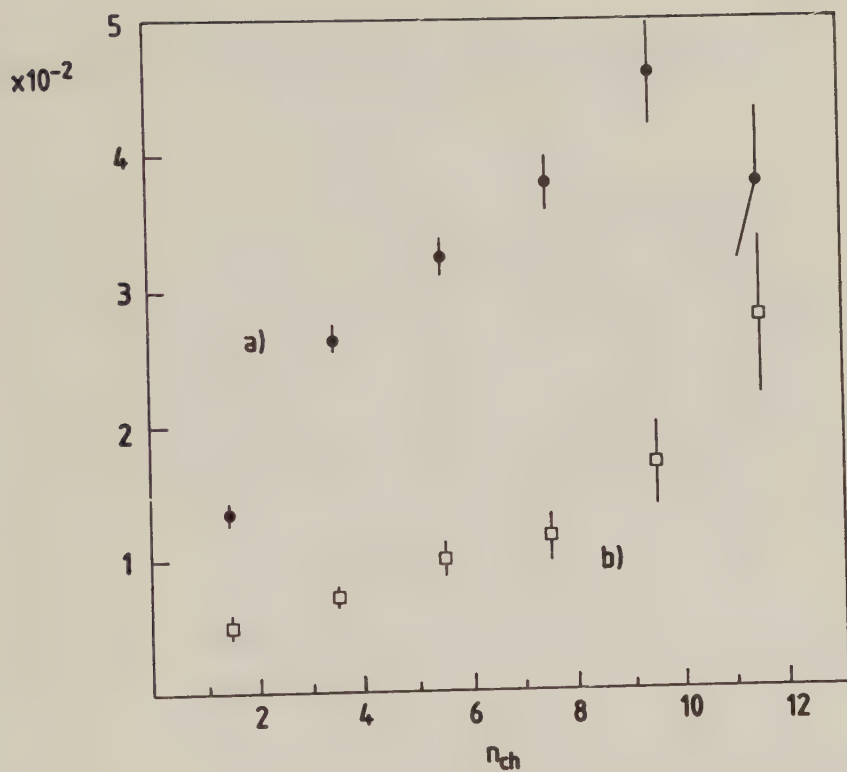


Fig. 10

INCLUSIVE VECTOR-MESON PRODUCTION IN THE CENTRAL REGION OF pp COLLISIONS AT $\sqrt{s}=63$ GeV

The Axial Field Spectrometer Collaboration

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Production of ρ^0 , K^{*0} , $\bar{K}^{*0}$, and ϕ have been measured in proton–proton collisions at the CERN Intersecting Storage Rings (ISR) at low p_T in the central region. The transverse mass spectra are well described by $\exp(-a\mu_T)$, with $a = -6.4 \pm 0.2 \text{ GeV}^{-1}$. The cross sections for $d\sigma/dy|_{y=0}$ are $6.5 \pm 0.8 \pm 1.2 \text{ mb}$ for ρ^0 , $1.9 \pm 0.3 \pm 0.3 \text{ mb}$ for K^{*0} , $1.9 \pm 0.3 \pm 0.3 \text{ mb}$ for $\bar{K}^{*0}$, and $0.60 \pm 0.12 \pm 0.13 \text{ mb}$ for ϕ , where the first error is statistical and the second is systematic.

1. Introduction

We have measured inclusive vector-meson spectra at the CERN Intersecting Storage Rings (ISR) at $\sqrt{s}=63$ GeV for $|y|<1$ and transverse momentum (p_T) up to $1.5 \text{ GeV}/c$. Experimental data for vector mesons are relatively scarce at these energies, in particular in the central region [1]. At lower energies, however, their production has been more systematically investigated [2].

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Previous results indicate that in high-energy hadron collisions vector-meson production dominates over the production of pseudoscalar mesons. This is in qualitative agreement with spin statistics [3] which predict that most observed particles are decay products of vector-meson resonances. More detailed quark-parton models give quantitative predictions on the behaviour of vector-meson production [4]. Furthermore, it is of interest to know how much of the short-range correlations in hadron collisions can be explained by vector mesons.

The paper is organized as follows. In sects. 2 and 3 we describe the apparatus and the data analysis, and in sect. 4 the results are given.

2. Experimental set-up

The experiment was performed using the Axial Field Spectrometer (AFS) shown in fig. 1. The magnet provides an azimuthally symmetric field of ~ 0.5 T over the central region containing the track chambers. These cylindrically symmetric drift chambers are divided into two parts, to accommodate supports for the beam pipe. They are 1.42 m in length, and extend radially from 0.20 to 0.80 m from the intersection point. The material traversed by a charged particle before entering the drift chamber amounts to 0.045 radiation lengths, coming predominantly from the stainless-steel beam pipe (at 12 cm) and an inner scintillator hodoscope (at 18 cm).

The drift chamber is described in detail elsewhere [5]. Briefly, it is a single-gas-volume chamber operating at atmospheric pressure with a mixture of argon (50%) + ethane (50%). Each half chamber (fig. 1) consists of 41 sectors, of 4° width, leaving dead regions of 8° width up and down in azimuth. Each sector has 42 radially distributed sense wires oriented parallel to the magnetic field, and organized into three groups or "crowns". The wires are staggered ± 0.4 mm azimuthally to remove left-right ambiguities. The drift-time information is complemented by pulse heights recorded from both ends of the sense wires and used to obtain the position along the wire by charge division as well as the particle identity by ionization. The drift times give an average resolution of $230 \mu\text{m}$, and the charge division ~ 1.5 cm, after correcting for effects such as bending of the electron drift paths by the magnetic field, differences in electronic delays, and time-slewing effects caused by finite thresholds in the electronics. The resulting momentum resolution in the central part of the drift chamber is given approximately by $\delta p/p = \sqrt{(0.025p)^2 + (0.01)^2}$ (p in GeV/c), where the first term comes from measurement errors and the second from multiple scattering in the chamber gas and wires.

The event time was recorded using the cylindrical scintillator hodoscope, placed between the vacuum pipe and the drift chamber. Timing on the inner hodoscope is also used to reject multiple events, occurring within the read-out window of ± 600 ns. Two sets of scintillators were placed in the forward regions ($1.2^\circ < \theta < 6^\circ$) to monitor the luminosity and for use in the trigger. The trigger required a coincidence between these forward counters or a hit in the central scintillator

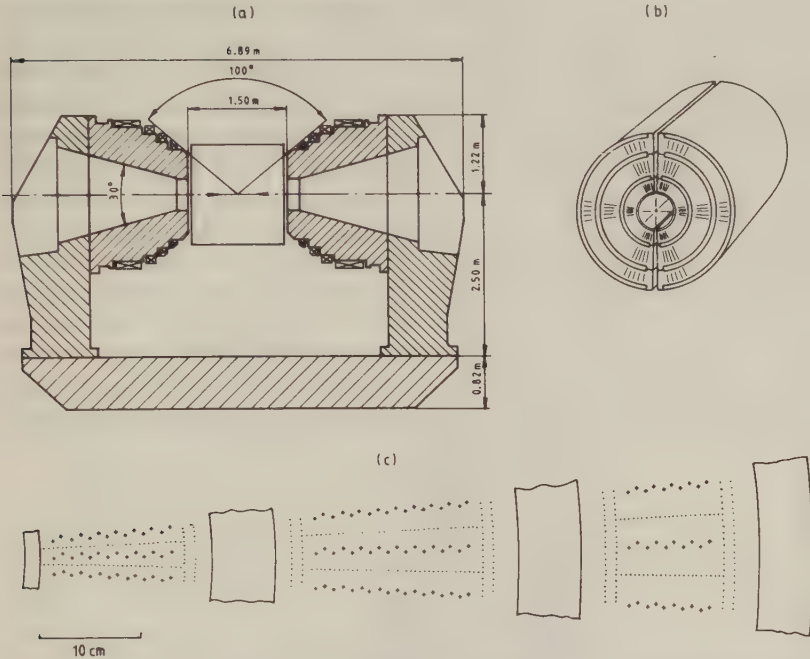


Fig. 1. (a) Schematic drawing of the Axial Field Magnet and the vertex drift chamber. (b) End view of the drift chamber. (c) Expanded view of a sector structure. The staggering of the sense wires, shown as crosses, has been exaggerated by a factor of five.

hodoscope (minimum bias trigger). This trigger records $\sim 90\%$ of the inelastic cross section.

3. Data analysis

This analysis is based on $\sim 2 \times 10^5$ triggers as defined in the previous section. The events were passed through a track-reconstruction program, which found track candidates in space (r, ϕ, z) . Events containing at least one track candidate were then passed through a fitting program to determine the track parameters, using the spline method [6]. The track parameters and errors were then used to estimate a common vertex position, and associate a subset of all reconstructed and fitted tracks with the event. From the initial sample 9×10^4 events contained a vertex.

All tracks in the remaining sample were required to originate from the event vertex, and contain 10 or more space points. These cuts were necessary to reduce contamination from background sources such as beam-pipe interactions, upstream beam-gas interactions and old hits in the drift chambers. In addition, we required

a $\chi^2/\text{degree of freedom} < 3.0$ for the single-track fits. This was particularly useful for rejecting errors introduced earlier at the track-reconstruction stage. A final selection was applied on the measurement errors of the individual track parameters.

Particles in this sample were identified using the information on the ionization from the drift chamber. The ionization for a track was defined as the mean value of the lower 70% of the individual pulse heights. Fig. 2 shows the truncated mean

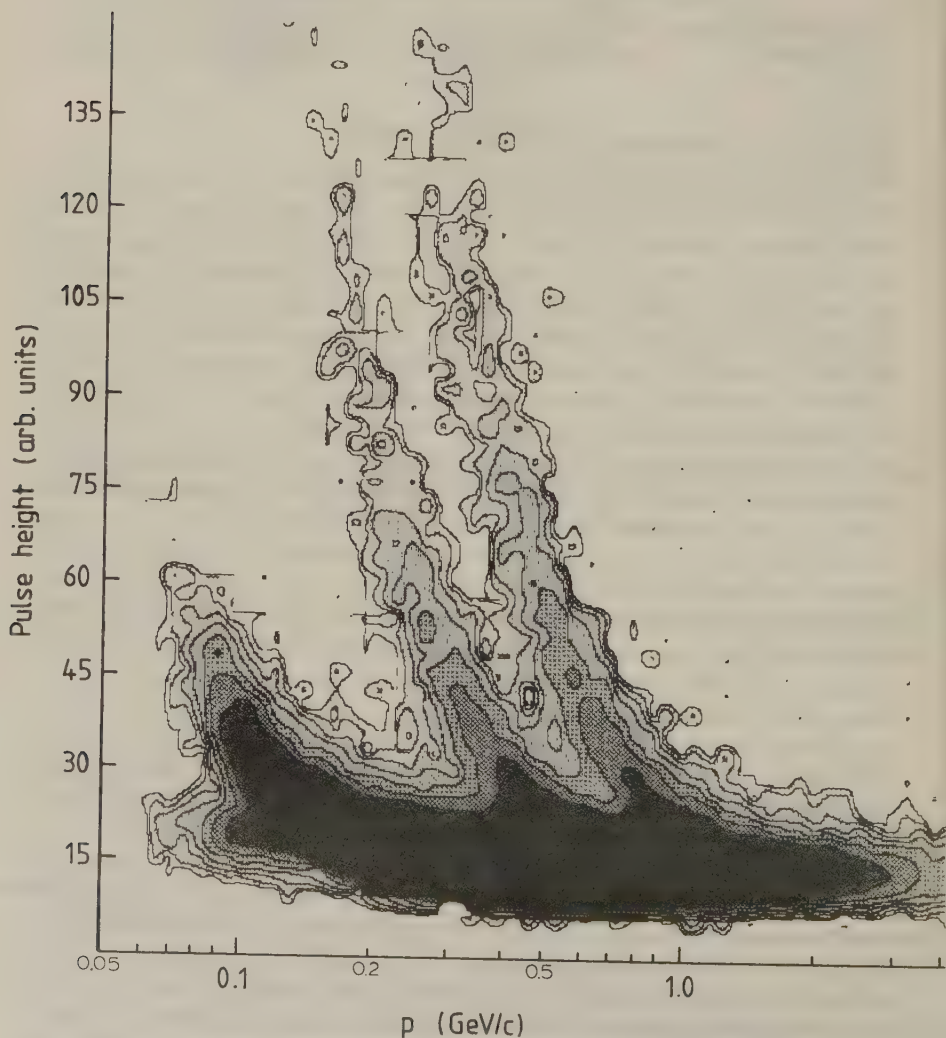


Fig. 2. dE/dx identification: truncated mean pulse height versus the momentum for negative particles. The contours represent a factor 2 in density.

pulse height versus track momentum for negative particles. Each particle type appears clearly. Particles were defined as kaons in a region of this plot where the contamination from other particles is $<5\%$.

The single-particle acceptance as a function of particle type (either kaon or any hadron), charge, rapidity, p_T , and azimuth for the observed particles was deduced by comparing their densities with previously measured spectra [7]. The detection efficiency with the chosen cuts for all hadrons rises to a level of $\sim 50\%$ for $p_T > 300$ MeV/c and remains approximately constant. Kaon efficiencies rise to a peak value of $\sim 40\%$ at a p_T of ~ 400 MeV/c, and drop to zero at approximately 700 MeV/c, as dE/dx separation fails. We estimate the systematic uncertainty in acceptance introduced by this technique to be 15% and 5% for kaons and hadrons, respectively. These errors arise predominantly from the normalization and our representation of the previous measurements.

To translate these single-particle acceptances into detection efficiencies for two-body vector-meson decays, we employed a Monte Carlo technique. Vector mesons

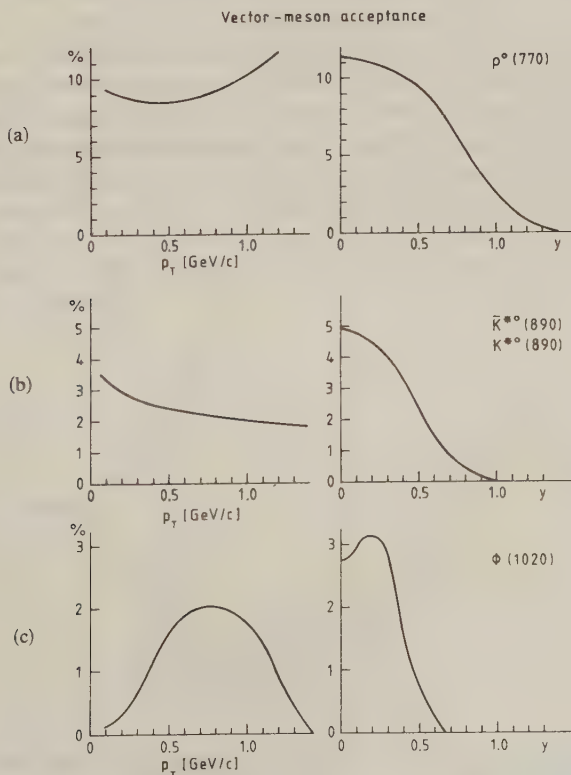


Fig. 3. Vector-meson acceptances as a function of p_T and rapidity: (a) ρ^0 ; (b) K^{*0} ; (c) ϕ .

were generated with a P-wave Breit-Wigner distribution. They were assumed to be produced unpolarized, with y and p_T distributions consistent with the measured differential cross sections quoted later. It was checked that there was no azimuthal variation of the vector mesons and that the decay was indeed isotropic. The momenta of the decay particles were smeared with the detector resolution. The vector meson was then given a weight equal to the product of the acceptances derived from the single-particle acceptance tables. The resulting vector-meson acceptances are shown in figs. 3a-c for ρ^0 , K^{*0} , and ϕ , as a function of p_T and y . The acceptance calculated from uncorrelated single-particle spectra does not fully account for losses in the detector introduced by the two-body kinematics of the decays. We have estimated such effects to be $<1\%$, $<1\%$, and $\sim 4\%$ for ρ , K^* , and ϕ , respectively, and have included these uncertainties in our acceptance errors.

The invariant masses of $\pi^+\pi^-$ and $K^\pm\pi^\pm$ were formed. The mass spectra are shown in figs. 4a and 5a, where the solid line represents the shape of the uncorrelated background determined by combining particles from alternate events of the same multiplicity. Background shapes constructed in this way also agree well for $\pi^\pm\pi^\pm$ combinations. For ρ^0 and K^{*0} , the background-shape normalization was chosen to remain positive in the regions surrounding the signals after subtraction. For the ρ^0 this was obtained by normalizing above $2 \text{ GeV}/c^2$, while for the K^* the lack of statistics in the high-mass tail of the $K\pi$ spectrum forced an arbitrary normalization. The resulting spectra are shown in figs. 4b and 5b, where prominent ρ^0 and K^{*0} signals appear. The narrow peak at $0.5 \text{ GeV}/c$ in fig. 4b is due to K_S^0 with decay vertices indistinguishable from the primary vertex.

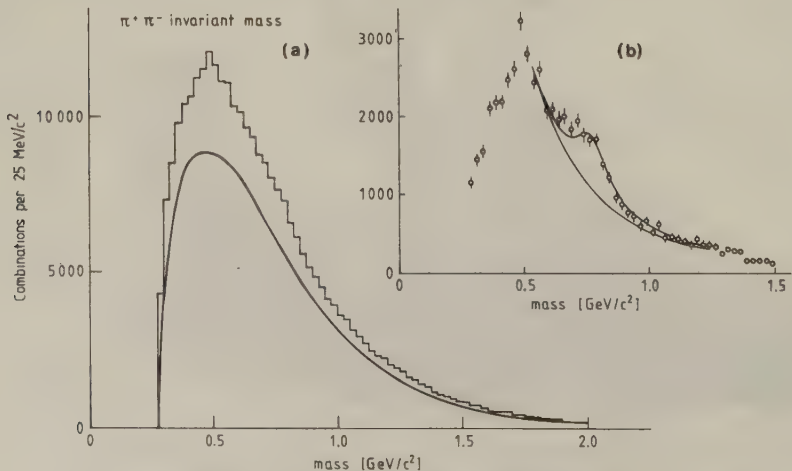


Fig. 4. $\pi^+\pi^-$ invariant mass spectra. (a) Combinations within the same event. The full line describes the non-resonant background determined by mixing events. (b) The background-subtracted signal. Fitted curves are described in the text.

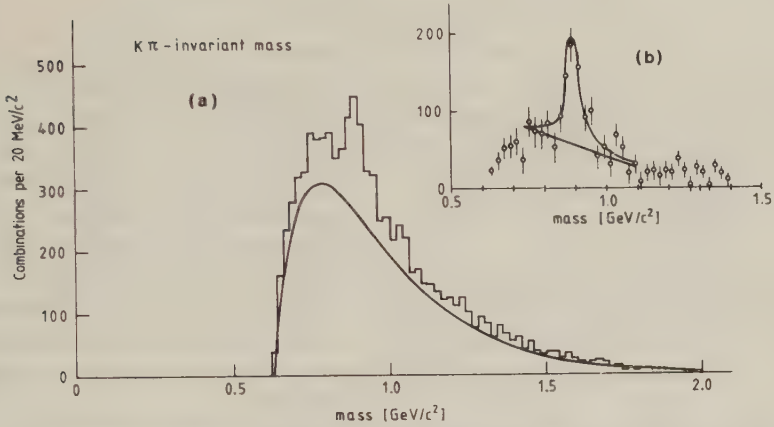


Fig. 5. $K^+\pi^+$ invariant mass spectra. (a) Combinations within the same event. The full line describes the non-resonant background determined by mixing events. (b) The background-subtracted signal. Fitted curves are described in the text.

A fit to each subtracted mass distribution was performed using a P-wave Breit-Wigner formula with nominal mass and width, together with an assumed exponential non-resonant correlation background in the ρ^0 case, and a linear form for the K^{*0} . We have found that the shape uncertainties in resonance and background forms lead to changes of less than 15% and 4% in the ρ^0 and K^{*0} signals, respectively, while still retaining acceptable fits.

Fig. 6 shows the K^+K^- invariant mass spectrum. The ϕ resonance is well fit by a Breit-Wigner of width 10 MeV/c² (consistent with the detector resolution) and a constant background.

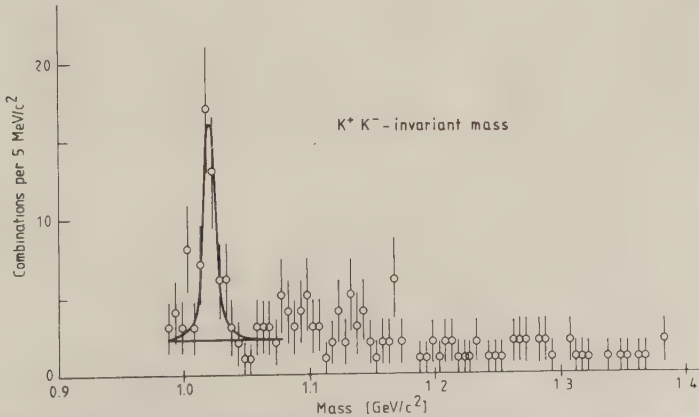


Fig. 6. K^+K^- mass spectra for all combinations. The curve is a fit to a Breit-Wigner together with a constant background.

TABLE 1
 ρ^0 data: cross section versus p_T

p_T (GeV/c)	$\langle p_T \rangle$ (GeV/c)	$\langle \mu_T \rangle$ (GeV/c)	$E(d^3\sigma/dp^3)$ (mb/GeV ²)	χ^2/NDF
0.00–0.25	0.17	0.79	$7.8 \pm 0.8 \pm 1.4$	33/25
0.25–0.50	0.38	0.86	$3.85 \pm 0.41 \pm 0.69$	31/25
0.50–0.75	0.62	0.99	$1.94 \pm 0.19 \pm 0.35$	30/25
0.75–1.00	0.86	1.15	$0.64 \pm 0.09 \pm 0.12$	26/28
1.00–1.50	1.15	1.37	$0.17 \pm 0.02 \pm 0.03$	29/25

TABLE 2
 K^{*0} data: cross section versus p_T

p_T (GeV/c)	$\langle p_T \rangle$ (GeV/c)	$\langle \mu_T \rangle$ (GeV/c)	$E(d^3\sigma/dp^3)$ (mb/GeV ²)	χ^2/NDF
0.00–0.25	0.17	0.91	$1.97 \pm 0.51 \pm 0.35$	22/18
0.25–0.50	0.38	0.97	$0.96 \pm 0.23 \pm 0.17$	26/18
0.50–0.75	0.62	1.08	$0.65 \pm 0.16 \pm 0.12$	17/18
0.75–1.00	0.86	1.24	$0.26 \pm 0.07 \pm 0.05$	23/18
1.00–1.50	1.15	1.45	$0.033 \pm 0.022 \pm 0.006$	17/18

TABLE 3
 $\bar{K}^{*0}$ data: cross section versus p_T

p_T (GeV/c)	$\langle p_T \rangle$ (GeV/c)	$\langle \mu_T \rangle$ (GeV/c)	$E(d^3\sigma/dp^3)$ (mb/GeV ²)	χ^2/NDF
0.00–0.25	0.17	0.91	$1.41 \pm 0.51 \pm 0.25$	23/18
0.25–0.50	0.38	0.97	$1.12 \pm 0.23 \pm 0.20$	20/18
0.50–0.75	0.62	1.08	$0.52 \pm 0.16 \pm 0.09$	16/18
0.75–1.00	0.86	1.24	$0.16 \pm 0.07 \pm 0.03$	9/18
1.00–1.50	1.15	1.45	$0.050 \pm 0.024 \pm 0.009$	23/18

TABLE 4
 ϕ data: cross section versus p_T

p_T (GeV/c)	$\langle p_T \rangle$ (GeV/c)	$\langle \mu_T \rangle$ (GeV/c)	$E(d^3\sigma/dp^3)$ (mb/GeV ²)
0.25–0.50	0.38	1.09	$0.22 \pm 0.12 \pm 0.05$
0.50–0.75	0.62	1.19	$0.17 \pm 0.05 \pm 0.04$
0.75–1.00	0.86	1.33	$0.061 \pm 0.023 \pm 0.015$
1.00–1.50	1.15	1.53	$0.023 \pm 0.011 \pm 0.006$

4. Results

The distributions of produced resonances have been studied as a function of transverse mass (μ_T) and rapidity (y). In determining absolute cross sections, we have included in the tables an overall systematic uncertainty of 20%, coming from our luminosity measurement (7%) and event selection criteria, in addition to the acceptance (correcting for unseen decay modes) and fitting errors. However, the errors shown in the figures are purely statistical.

The cross sections as a function of μ_T are summarized in tables 1 to 4 and displayed in fig. 7. These points were obtained by fitting the data to a Breit-Wigner distribution plus background for each p_T bin, as shown in fig. 8 for $\rho^0 \rightarrow \pi^+ \pi^-$. The inclusive spectrum for each resonance is well fitted by a simple exponential

$$E \frac{d^3\sigma}{dp^3} \propto \exp(-a\mu_T),$$

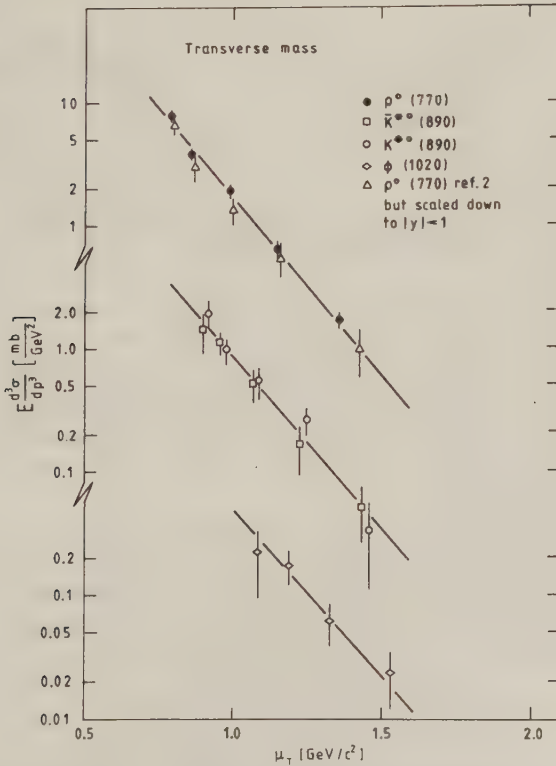


Fig. 7. $E(d^3\sigma/dp^3)$ as a function of transverse mass (μ_T) for ρ^0 , K^{*0} , $\bar{K}^{*0}$, and ϕ . The lines represent a global fit of the form $\exp(-a\mu_T)$.

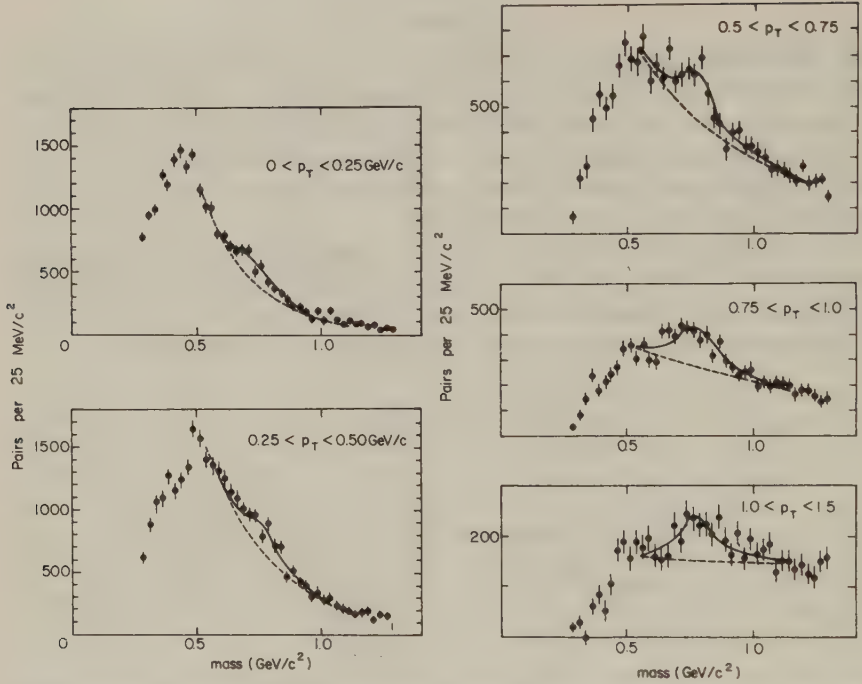


Fig. 8. Background-subtracted $\pi^+\pi^-$ invariant mass spectra in five bands of p_T , as used for determining the μ_T distribution of ρ^0 production.

with $a = 6.4 \pm 0.2 \text{ GeV}^{-1}$. The data can also be fitted to similar exponentials in p_T and p_T^2 . The results of these fits are presented in table 5. We see from fig. 7 that the μ_T distribution for the ρ^0 is in agreement with the previous measurements of ref. [1] at the same c.m. energy, but rescaled to the same rapidity region.

Table 5 also gives the cross sections integrated over p_T , namely $d\sigma/dy$ for $0 < y < 1$. The data are consistent with no variation with rapidity over the limited range covered by this experiment.

The ratio of $\langle \rho^0 \rangle / \langle \pi^- \rangle$ is shown in fig. 9 as a function of p_T . The rise of this curve from ~ 0.0 at low p_T levels to a level of ~ 0.7 at $p_T \sim 1.2 \text{ GeV}/c$ appears to be approaching the similarly high ratio of 0.87 ± 0.17 previously measured for $\langle \omega \rangle / \langle \pi^0 \rangle$ at $\sqrt{s} = 63 \text{ GeV}$ with $p_T > 3$ and $y = 0$ [8]. In addition, the following particle ratios have been extracted from the data, in the range $p_T < 1.5$, $|y| < 1$:

$$\langle \rho^0 \rangle / \langle \pi^- \rangle = 0.20 \pm 0.03 \pm 0.04,$$

$$\langle \bar{K}^{*0} \rangle / \langle K^- \rangle = 0.64 \pm 0.09 \pm 0.03,$$

$$\langle K^{*0} \rangle / \langle K^+ \rangle = 0.55 \pm 0.08 \pm 0.03,$$

$$\langle \phi \rangle / \langle \rho^0 \rangle = 0.09 \pm 0.02 \pm 0.02,$$

TABLE 5
Results ^{a)} of fits to the cross sections

Fit	<i>A</i> exp ($-a\mu_T$)			<i>B</i> exp ($-bp_T$)		
	<i>A</i> (mb GeV ⁻²)	<i>a</i> (GeV ⁻¹)	χ^2 /NDF	<i>B</i> (mb GeV ⁻²)	<i>b</i> (GeV ⁻¹)	χ^2 /NDF
ρ^0	1083±55	6.4±0.3	2.8/3	16.6±0.8	3.9±0.1	7.8/3
K^{*0}	671±87	6.6±0.8	2.3/3	4.0±0.9	3.7±0.4	4.0/3
$\bar{K}^{*0}$	573±52	6.5±1.0	0.3/3	3.5±0.8	3.5±0.4	2.6/3
ϕ	103±15	5.5±1.4	0.4/2	0.91±0.56	3.1±0.7	0.8/2
ρ^0	1085±265	6.4±0.2	6/14	16.0±1.4	3.8±0.1	17/14
K^{*0}	561±162			4.0±0.6		
$\bar{K}^{*0}$	532±155			4.3±0.6		
ϕ	321±114			1.4±0.3		

Fit	<i>C</i> exp ($-cp_T^2$)			$d\sigma/dy(0 < y < 1)$ (mb)
	<i>C</i> (mb GeV ⁻²)	<i>c</i> (GeV ⁻²)	χ^2 /NDF	
ρ^0	6.5±0.3	3.0±0.1	10/3	6.5±0.8±1.2
K^{*0}	1.7±0.3	2.9±0.4	1.7/3	1.94±0.28±0.35
$\bar{K}^{*0}$	1.6±0.3	2.9±0.5	0.6/3	1.87±0.28±0.34
ϕ	0.33±0.13	2.1±0.6	0.4/2	0.58±0.12±0.13
	6.33±0.3	2.9±0.1	14/14	
	1.6±0.2			
	1.7±0.2			
	0.48±0.10			

^{a)} The errors in *A*, *B*, and *C* are statistical only and do not contain possible normalization errors of 7%.

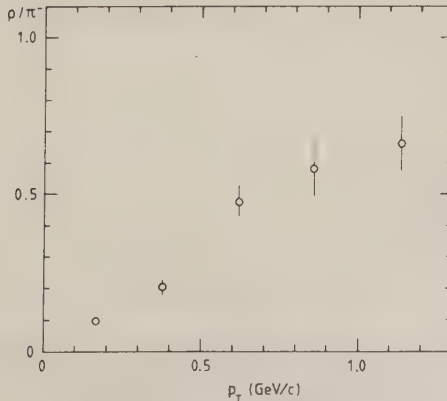


Fig. 9. p_T dependence of ρ/π^- .

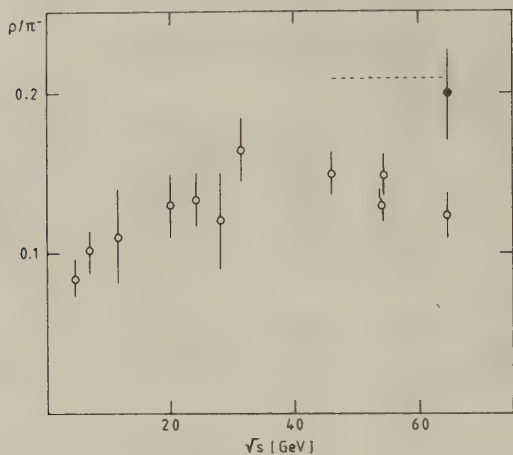


Fig. 10. ρ/π^- as a function of $\sqrt{s}$: ● – this experiment; ○ – refs. [1, 2].

where the first error is statistical and the second is systematic. These particle ratios are shown in figs. 10 and 11, together with lower energy data covering larger rapidity. The dashed lines in these plots indicate a quark-model prediction based on spin statistics [3]. Assuming isospin invariance and equal production of ρ^0 and

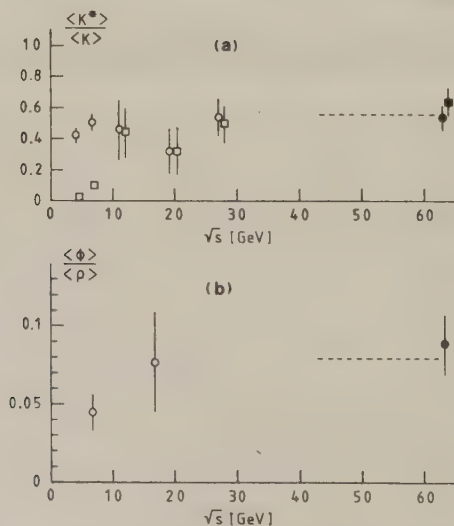


Fig. 11. (a) K^*/K as a function of $\sqrt{s}$: ■ $\bar{K}^{*0}/K^-$, ● K^{*0}/K^+ – this experiment; □ K^{*+}/K_S^0 , ○ K^{*+}/K_S^0 – ref. [2]. (b) ϕ/ρ as a function of $\sqrt{s}$: ● – this experiment; ○ – ref. [2]. The dashed lines are predictions from ref. [3] for the central region.

ω , the above ratios imply that $\sim(60 \pm 15)\%$ of all pseudoscalar mesons are decay products of vector mesons.

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Inclusive vector-meson cross-sections in proton-
proton collisions for $|y| < 1.0$ at
 $\sqrt{s} = 53$ and 63 GeV

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Abstract

Absolute cross-sections for the inclusive production of ρ^0 , K^* , K^{*0} and ϕ in pp and pp collisions at the CERN ISR are given for $|y| < 1.0$ at $\sqrt{s} = 53$ and for pp collisions at 63 GeV.

1. Introduction

In a previous paper (1) we presented a comparison of hadron production in proton-proton and proton-antiproton collisions in the central region at $\sqrt{s} = 53$ GeV. The two data sets used in the comparison were subject to the same geometrical constraints and background conditions. A detailed knowledge of the acceptance and reconstruction efficiency was therefore unimportant. In this paper these effects have been evaluated to give an absolute normalization of the data. Moreover, an earlier analysis of vector-meson production at $\sqrt{s} = 63$ GeV (2) has been repeated using the present program chain and with different input for the parametrization of the inclusive cross-section of kaons (4,5).

2. Trigger selection and data analysis

The data was collected with the cylindrical drift chamber of the Axial Field Spectrometer (3). The 1.4 m long drift chamber is situated in an axially symmetric field of 0.5 T. A cylindrical barrel hodoscope (IH) surrounding the intersection region at a radius of 18 cm provided a signal for charged particles produced within $|y| < 2.0$. Large forward hodoscopes (BB) on either side of the intersection, covering the angular range of $1.2^\circ < \theta < 6.0^\circ$, provided signals for particles emitted in the forward regions. The details of the apparatus is described in (1) and (2). All data referred to here were taken with loose trigger conditions ("minum bias").

There is a small difference in the trigger selection of the events between the two energies. At $\sqrt{s} = 53$ GeV only BB was used in the trigger, while for $\sqrt{s} = 63$ GeV either IH or BB was used. This trigger recorded 90% of the inclusive cross-section while the BB alone is sensitive to 60 % of total inclusive cross-section. To make sure that the different trigger criteria do not constitute any bias to the result, the IH and BB triggers were studied separately in the $\sqrt{s} = 63$ GeV data. Fig 1 shows the transverse momentum spectra for charged hadrons (a) and kaons (b) for the two cases. There is no difference between the spectra.

The $\sqrt{s} = 53$ GeV data sample consists of 172k pp and $\bar{p}p$ events each and the 63 GeV data of 200k pp collisions, which were reconstructed using the pattern recognition and geometry programs (6) developed for the AFS. The luminosities were about $10^{28} \text{ cm}^{-2} \text{ s}^{-1}$ for both the pp and $\bar{p}p$ data at $\sqrt{s} = 53$ GeV and $2 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ at 63 GeV. In the following only the pp data will be discussed.

Results from the $\sqrt{s} = 63$ GeV sample has been published in (2). However, in order to eliminate possible systematic differences between the energies, due to changes in the reconstruction and analysis procedure, this data was reanalysed.

The events were required to contain a reconstructed vertex, if there were more than one track seen in the drift chamber. After this there remains 136k events at 53 GeV and 103k events at 63 GeV. Due to the high luminosity at 63 GeV a large fraction of the events were rejected as multiple events, using the timing information from the IH. All tracks were required to originate from the interaction vertex. This removes about 25% of the true tracks. These suffer mainly from imprecision in the charge division measurement in the drift chamber. For events with only one seen track, this track was required to extrapolate to the interaction diamond.

To ensure good track quality, requirements on the measurement errors were made. The track quality differs in the two data samples. This can be seen from fig 2, where the acceptances for charged particles are obtained from a comparison with the inclusive differential cross-section as obtained by the British-Scandinavian collaboration (4).

The kaons were identified as in (1), using the ionization measurements from the drift chamber. Somewhat harder cuts on the kaon identification was made in the previous analysis at $\sqrt{s} = 63$ GeV (2). The charged kaon acceptances were evaluated by comparing the observed spectra with measured cross-sections (4,5). The best inclusive data on low momentum kaon production at $y = 0$ is that of ref 5, but their range in p_T is limited ($p_T < 0.3$). The old analysis used a common fit in transverse mass to this data (5) and the British-Scandinavian data (4) at $\sqrt{s} = 63$ GeV. Here we also give results using the parametrization from (5) of the low momentum region alone, extrapolated to the higher momentum region (fig 3a-b). Fig 3 also includes the observed kaon-spectra and the kaon-spectra expected from ϕ decay. It is obvious that the acceptance depends on how well the kaon cross-section is known at transverse momenta up to 0.5 GeV.

The vector-meson acceptances were evaluated by Monte-Carlo where resonances were generated with a relativistic P-wave Breit-Wigner mass distribution. They were assumed to have the same transverse mass dependence as in (2) and to be constant in rapidity and azimuth. The acceptance was taken as the product of the probability to detect each of the two particles from the decay.

All cross-sections are calculated with the formula $\sigma dN/N$ where σ is the total inclusive cross-section, dN is the amount of resonances observed and N the number of events used in the analysis. This assumes that the events which did not satisfy the trigger had the same probability for producing a vector-meson as those which did satisfy the trigger. N should correspond to the total number of events including events with one or zero tracks in the drift chamber, which gives a correction factor (0.7) to the number of events with a vertex. In the course of our present analysis we discovered that unfortunately this factor was applied twice in (2) giving a vector-meson acceptance a factor two too low, corresponding to cross-sections a factor 1.4 too high.

3. The ρ^0 meson

The two particle invariant mass was formed by calling all particles a pion. The uncorrelated background was estimated by combining particles from different events. Four different methods were tried to extract the ρ signal:

- A) raw spectra fitted to $(x-a)**b*\exp(-cx) +$ Breit-Wigner
- B) raw spectra fitted to $\exp(-cx) +$ Breit-Wigner
- C) background subtracted spectra fitted to $(x-a)**b*\exp(-cx) +$ Breit-Wigner
- D) background subtracted spectra fitted to $\exp(-cx) +$ Breit-Wigner

The spectra and fits at $\sqrt{s} = 53$ GeV are shown in fig 4. The results of the methods are given in table I, together with the corrected value from (2), which used method D. The errors are pure statistical. The good agreement between the results shows that there is no difference between the old and new program chain.

The energy dependence of the cross-section at $y = 0$ is shown in fig 7 using method D. The cross-section is seen to be fairly constant above $\sqrt{s} = 15$ GeV. As a comparison the cross-section in pp collisions is also shown.

As a further check on the equality between IH and BB triggered events, the number of ρ 's in the BB triggered events at $\sqrt{s} = 63$ GeV were extracted. $66 \pm 9\%$ of all ρ 's are from BB triggered events, and 66% is also the overall events containing a BB trigger.

4. The K^0 mesons

The invariant mass of $K\pi$ was formed by using the identified kaons and calling any other particle for a pion. Here only a fit of the form $(x-a)**b*\exp(-cx) +$ Breit-Wigner has been used. Fig 5 shows an example of a fit. Doing a background subtraction and using the $a + bx +$ Breit-Wigner fit gives exactly the same result - this was the method used in (2). The K^0 cross-sections have been calculated using the different representations of the kaon cross-sections from (4,5) as described above. Two different ways of extracting the the kaon acceptance have been tried:

- A) fit in transverse mass to the combined data from (4,5) only at 63 GeV
- B) R803-fit (5)

Table II gives the results.

There is good agreement in the cross-sections, within errors, between ref 2 and the present analysis (method A). However the different methods of extracting a clean kaon sample accounts for a small difference.

Fig 8 shows the variation with energy of $d\sigma/dy$ at $y = 0$ for pp and $\bar{p}p$ collisions (method B). There is a tendency for the cross-section to reach a plateau at a level around 1 mb.

5. The ψ meson

Only uniquely identified kaons were used. Fig 6 shows a spectrum with the fit $a + bx + \text{gaussian}$. The same methods were used as for K^* to extract the kaon-acceptances :

- A) fit in transverse mass to the combined data in (4 and 5) only at 63 GeV
- B) R803-fit (5)

The results are shown in table III together with the cross-section in $\bar{p}p$ collisions at 53 GeV using the ratio $\bar{p}p/pp$ from (1).

The highest cross-section for ψ is with the kaon acceptances derived from the fit to the combined data in ref 4 and 5 at 63 GeV. The value in (2) is a bit high compared with the value found in the present analysis. It can be shown that the measured cross-section depends on the analysis procedure. Applying the same track selection criteria as in (2) we get the ψ cross-section to $347 \pm 91 \mu\text{b}$ at $\sqrt{s} = 63 \text{ GeV}$ in agreement with (2), apart from a small effect due to different cuts for kaon identification. Performing the same procedure at 53 GeV does not produce any change in the measured cross-section. The systematic errors include uncertainty about the choice of the representation of the kaon cross-section and the uncertainty of the background below the ψ peak. The total systematic error is 20% at 53 GeV and 30% at 63 GeV.

The cross-sections as derived with a parametrization of the kaon cross-section from (5) agrees with the values as expected for ψ -production at Feynman $x = 0$ (7). The results are shown in fig 9 (assuming the same transverse mass dependence as in (2)).

6. Conclusions

The 63 GeV data published in (2) has been reanalysed and compared with new data at 53 GeV (1). The new values at 63 GeV are consistent with those in (2), after that a correction factor 0.7 has been applied. The cross-sections of ρ^0 , K^0 , $K^{\pm}$ and ψ at $y = 0$ do not show any strong energy dependence within the range of ISR energies (23-63 GeV).

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TABLE I. ρ^0 cross section in (mb) derived in four different ways as described in the text

	53 GeV	x2/ndf	63 GeV	x2/ndf	ref 2
A	3.4+-0.2	47/32	3.3+-0.3	35/32	-----
B	5.1+-0.4	18/25	5.6+-0.4	31/25	-----
C	3.4+-0.3	37/32	3.4+-0.4	31/32	-----
D	4.0+-0.3	13/25	4.4+-0.4	22/25	4.6+-0.5

TABLE II. K^*_0 and $\bar{K}^*_0$ cross-sections in (mb). Method A and B are described in the text

K^*_0			
	53 GeV	63 GeV	ref 2
x2/ndf	31/39	32/39	
A	-----	1.13+-0.20	1.36+-0.20
B	0.67+-0.11	1.06+-0.19	-----
$\bar{K}^*_0$			
	53 GeV	63 GeV	ref 2
x2/ndf	35/39	37/39	
A	-----	1.12+-0.20	1.31+-0.20
B	0.62+-0.11	1.02+-0.19	-----

TABLE III. ϕ cross-section in (μ b). Method A and B are described in the text. C is the cross-section in pp from the data in (1).

	53 GeV	63 GeV	ref 2
x2/ndf	8/12	6/12	
A	-----	269+-86	400+-80
B	158+-42	225+-72	-----
C	136+-44	-----	-----

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Figure captions

- 1 Observed p_T -distributions for IH and BB triggered events at $\sqrt{s} = 63$ GeV.
 a) charged hadrons (full line BB, dashed line IH)
 b) charged kaons (x BB, o IH)
- 2 charged hadron acceptance vs transverse momentum
 (x) $\sqrt{s} = 53$ GeV (•) $\sqrt{s} = 63$ GeV
- 3 a) K^+ cross-sections from (4) and (5) at $\sqrt{s}=63$ GeV
 full line is a parametrization from (4),
 dashed line from (5),
 dotted line is a fit in transverse mass using the
 combined data from (4) and (5) used in ref 2.
 The kaon distributions are the observed kaon spectra
 and kaons expected from ϕ decay
 b) K^+ cross-section at $\sqrt{s} = 53$ GeV
- 4 $\pi^+-\pi^-$ invariant mass distribution after
 subtracting an uncorrelated background ($\sqrt{s} = 53$ GeV)
- 5 $K^+\pi^-$ invariant mass distribution ($\sqrt{s} = 53$ GeV)
- 6 K^+-K^+ invariant mass distribution ($\sqrt{s} = 53$ GeV)
- 7 $\sqrt{s}$ dependence of $d\sigma/dy$ at $y = 0$ for p^0
 (•) pp collisions ref 8
 (◦) pp collisions ref 1,9
 (x) this experiment
 ref 1 ($\sqrt{s} = 53$ GeV) only gives ratios for $\frac{pp}{pp}$. The
 cross-sections given in this paper for pp collisions
 are multiplied with that ratio to get the cross-sections
 in pp collisions.
- 8 $\sqrt{s}$ dependence of $d\sigma/dy$ at $y = 0$ for $K^{\pm}$ (•, ◦)
 and K^* (▲, △)
 (•▲) pp collisions ref 8
 (◦△) pp collisions ref 1,9
 The values at 53 and 63 GeV are from this experiment.
 ref 1 ($\sqrt{s} = 53$ GeV) only gives ratios for $\frac{pp}{pp}$. The
 cross-sections given in this paper for pp collisions
 are multiplied with that ratio to get the cross-sections
 in pp collisions.
 The data point at $\sqrt{s} = 27.6$ GeV is taken at
 feynman $x = 0.05$
- 9 The ϕ cross-section vs feynman x .
 The value (◻) from Åkesson et. al. (1) is the
 uncorrected value. The new value from this analysis
 is also shown (■◆). The other values are from
 ◦ (7), ▼ (10), • (11), ▽ (12), * (13).
 The line represents a parton-fusion model calculation
 (11,14)

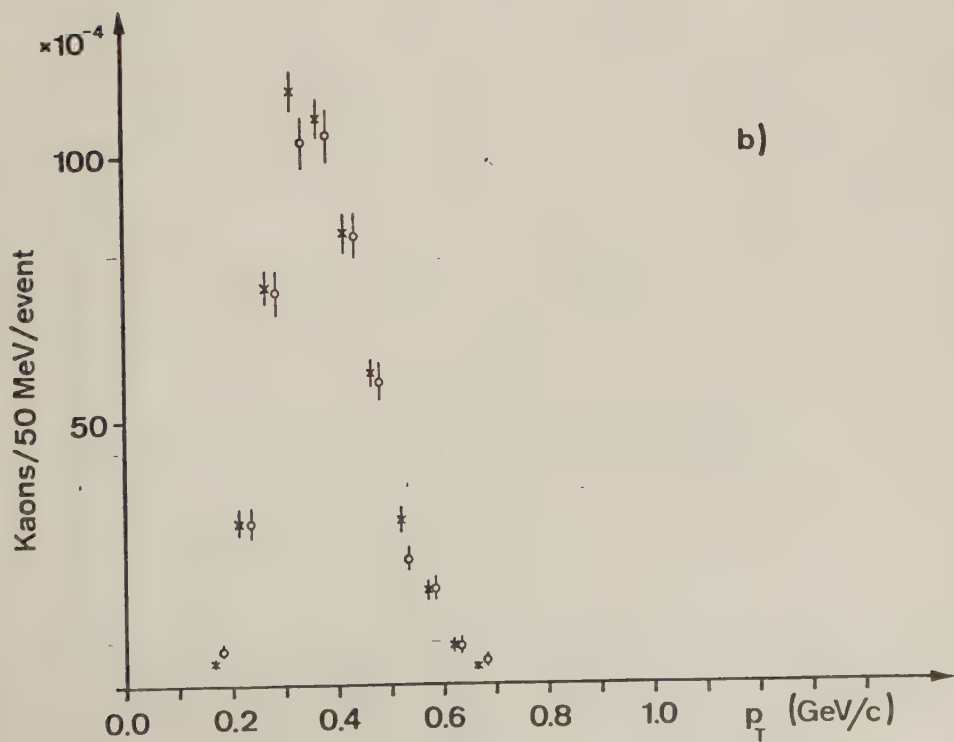
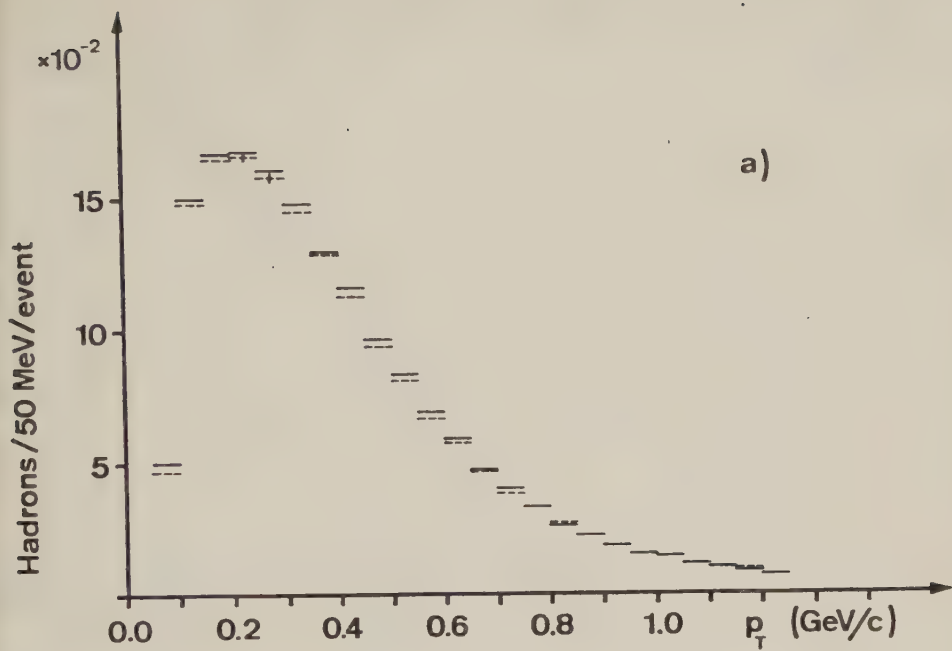


Figure 1

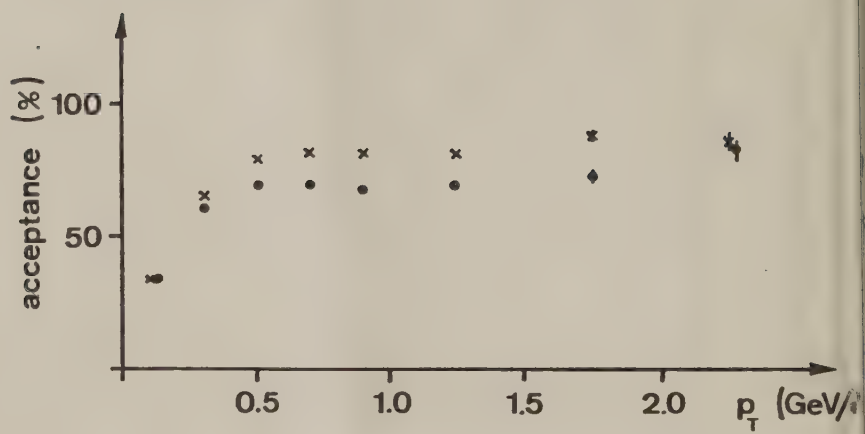


Figure 2

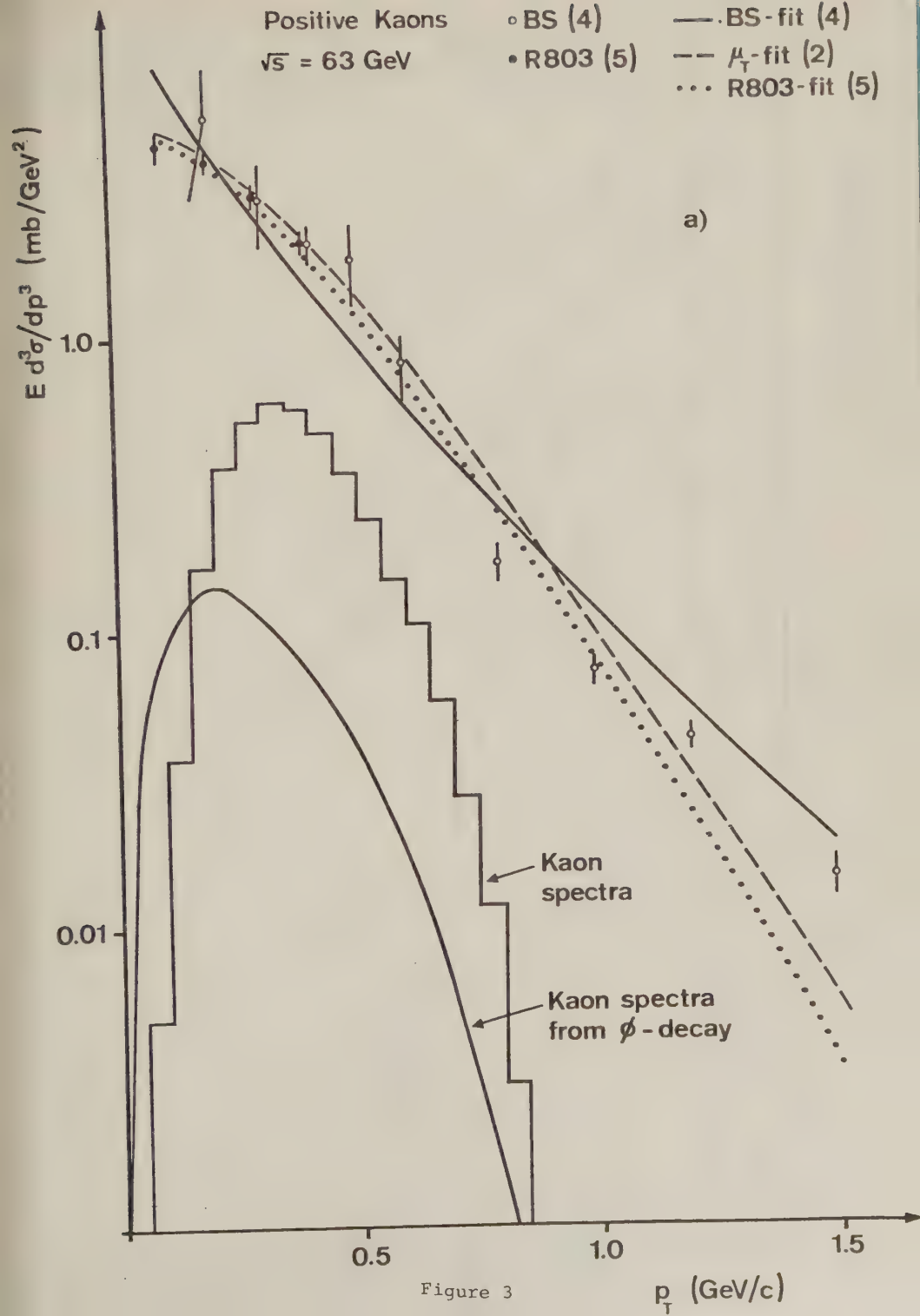


Figure 3

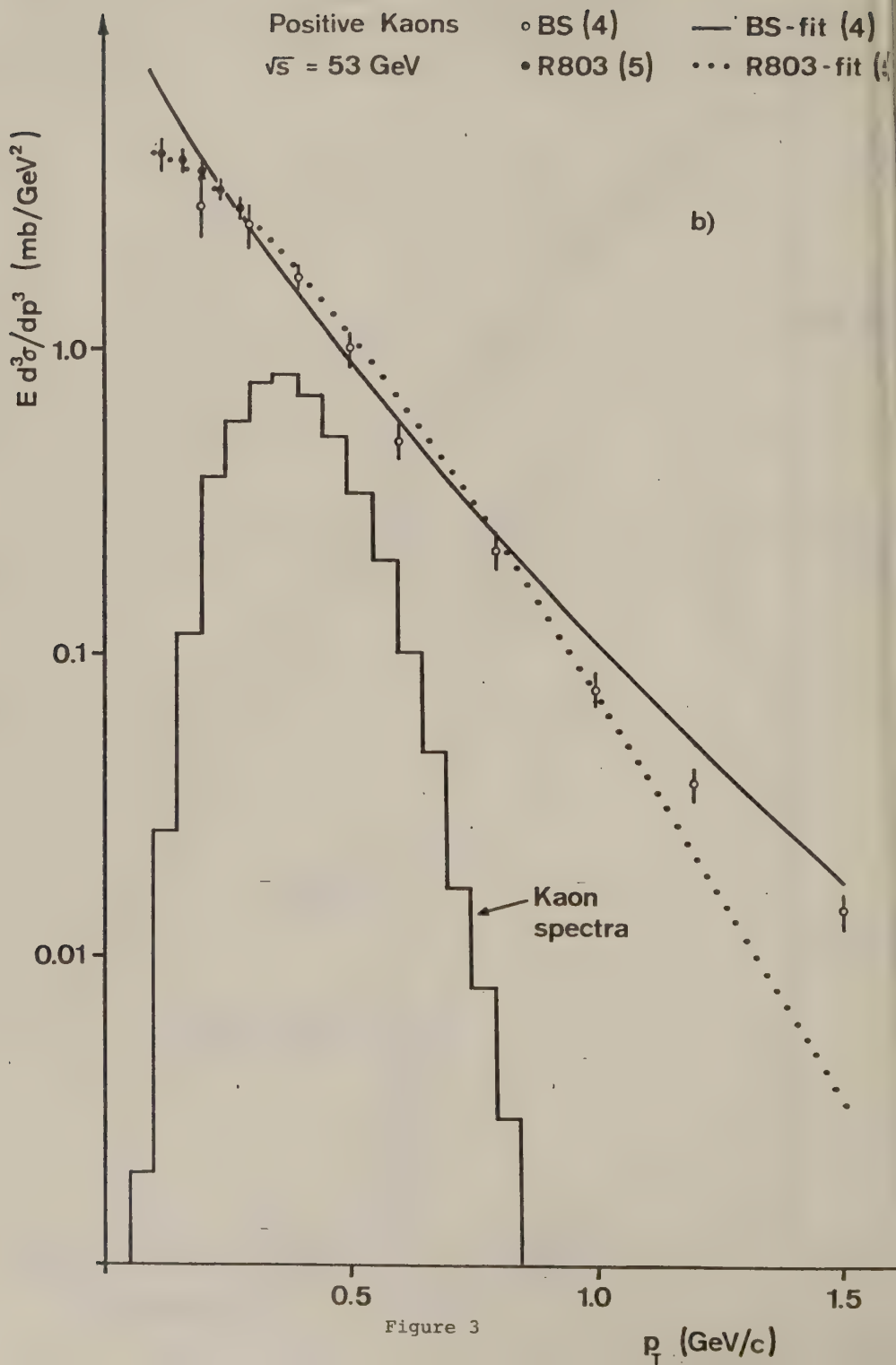


Figure 3

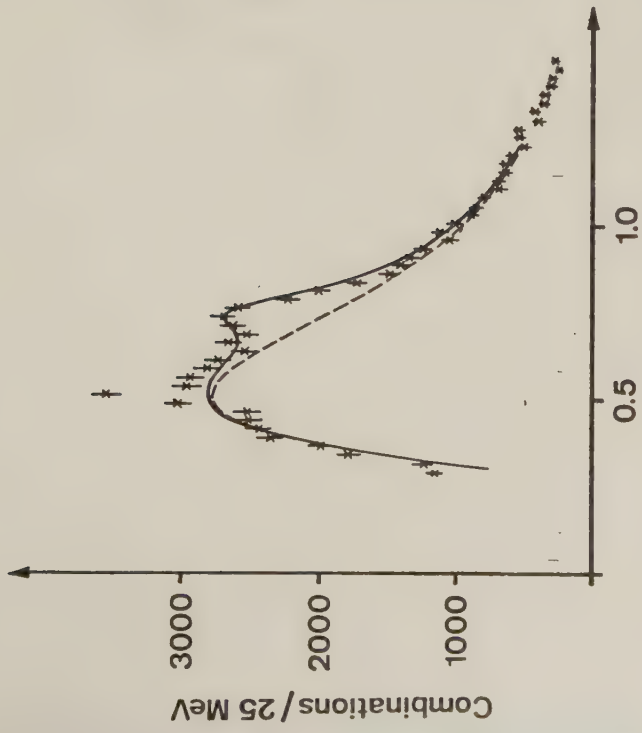
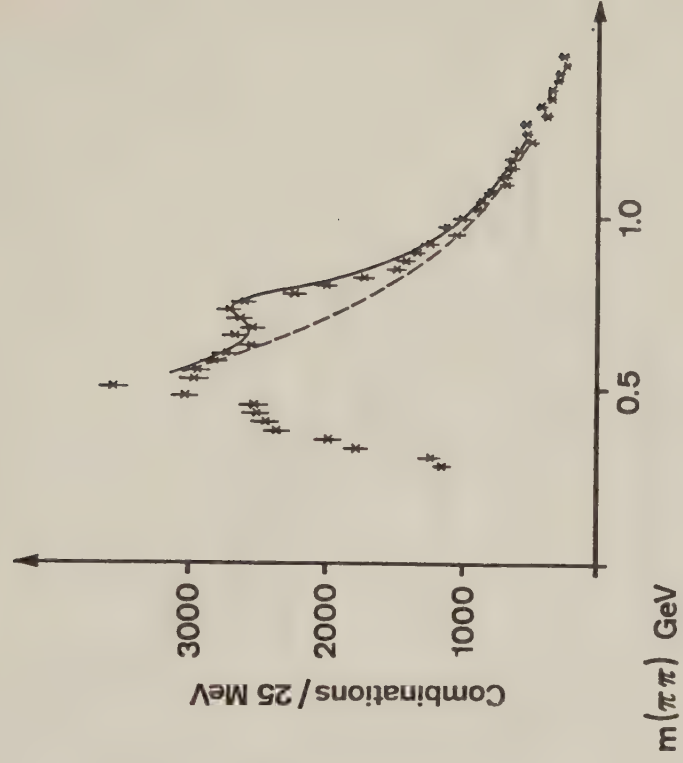


Figure 4



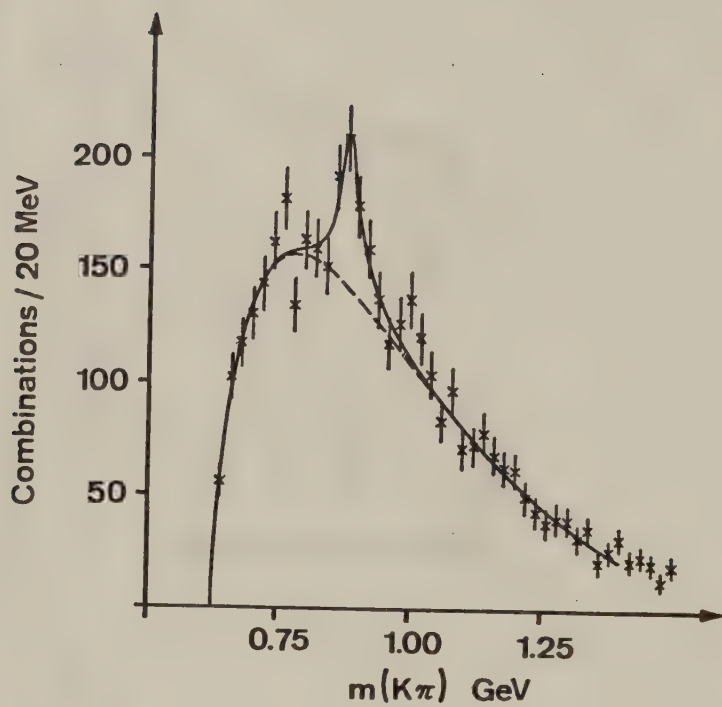


Figure 5

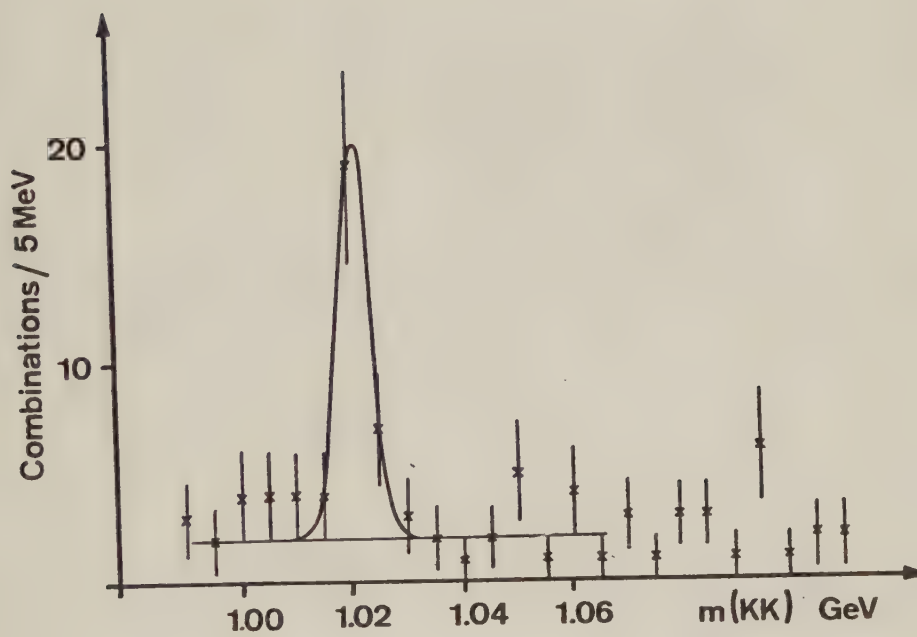


Figure 6

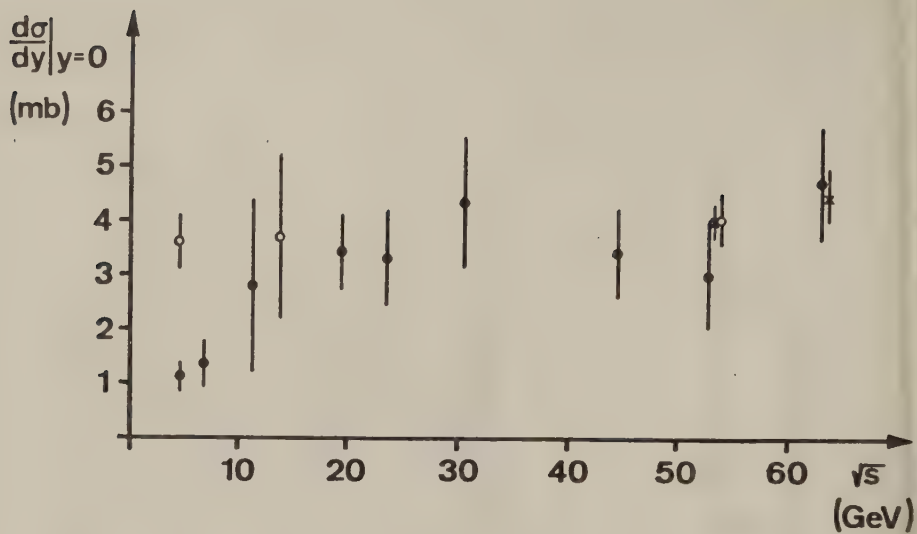


Figure 7

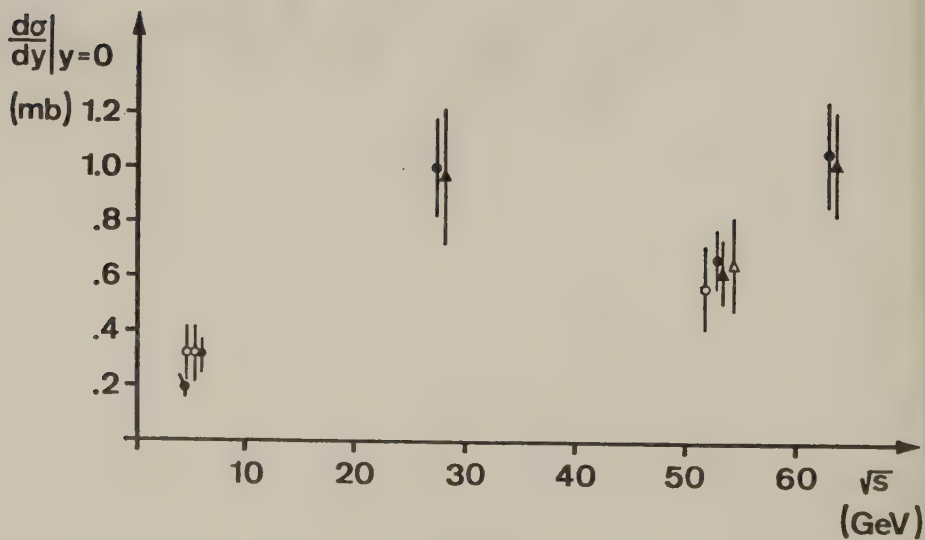


Figure 8

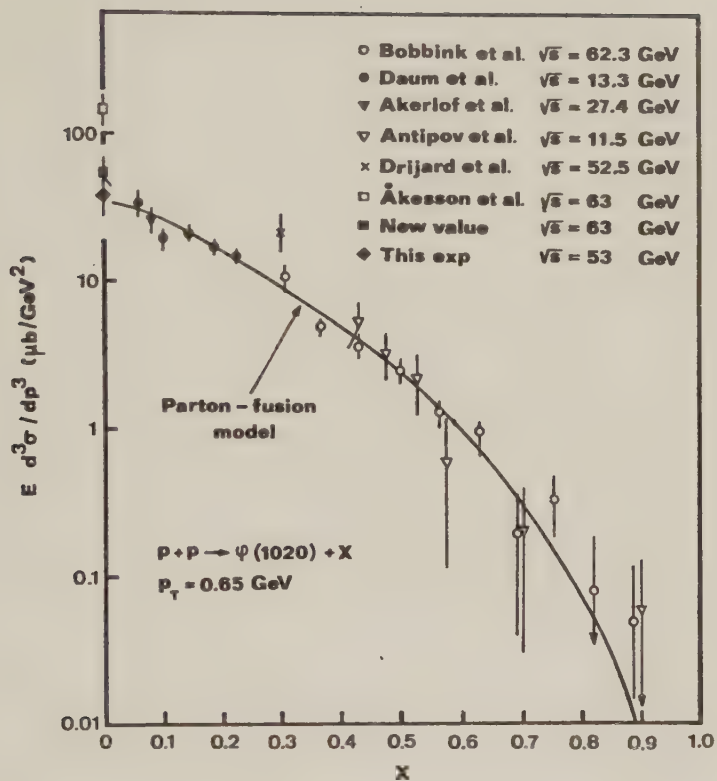


Figure 9

